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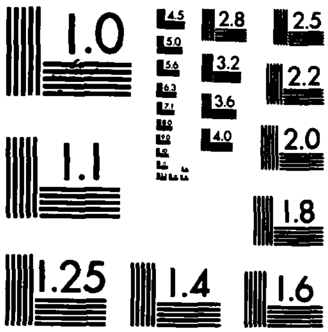

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OVERWASH PROCESSES AND FOREDUNE ECOLOGY, NAUSET SPIT, MASSACHUSETTS

by

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Many US east coast barrier beaches are retreating landward with sea level rise. This study provides quantitative information on the natural dynamics of barrier beaches along the North Atlantic coast. A geobotanical approach was utilized, which involved a detailed investigation of the physical transport processes, particularly overwash, and the vegetative response. A range of information was collected during different time frames, including short-term field measurements of overwash surges and vegetative quadrat data,
(Continued)

20. ABSTRACT (Continued).

historical analysis of the development of plant communities and morphological features, and a geologic evaluation of barrier evolution. These comprehensive baseline data on the natural dynamics of a northeast barrier beach can be used to delineate adverse effects of artificial stabilization, particularly dune-building activities.

All sections of the Nauset Spit system are subject to dramatic changes either by inlet activity or overwash. Each section along the barrier is eventually affected by these physical transport processes over the long term, culminating in landward barrier migration. Artificial creation and maintenance of dunes and salt marshes can be used to extend various periods of the migration cycle but will not alter the basic biogeological process. Without human intervention, new dunes and salt marshes will eventually become established along the barrier within the correct elevational ranges. However, there can be a considerable time lag due to the opportunistic conditions necessary for recolonization of barren washovers. Dune-building programs can effectively shorten the time necessary for revegetation and stabilization of the barrier landform. By working in association with natural processes, segments of the migrational cycle can be expanded but ultimately not restricted.

SUMMARY

Along the east coast of the United States, many barrier beaches are undergoing landward retreat as sea level rises. Human development of these barriers has resulted in increasing attempts to control natural processes with artificial stabilization. Understanding barrier island processes is an important first step in determining the results of stabilization. This report summarizes research undertaken to provide the scientific data necessary to understand the natural dynamics of a northeast barrier beach system.

Coastal research to date has focused on either ecological or geological processes; only a few projects have been designed to consider the interaction between vegetation and the physical factors which shape barrier beaches. This is the first detailed study undertaken to gather and analyze data on the effect of physical processes, principally overwash, on plant communities and physiographic features of barrier beaches in the Northeast.

Nauset Spit, Cape Cod, Mass., was chosen for this investigation because overwash has frequently occurred along this retreating shoreline, and historical information is available for almost 400 years. The Nauset Spit system developed from the deposition of material eroded from glacial cliffs and transported southward by littoral currents. This barrier beach system was formed by spit elongation over the past 5,000 to 7,000 years. The spit system has continued to evolve and has migrated landward, constantly reducing the overall dimensions of the enclosed bays. Nauset Spit is dependent on the eroding headland (glacial) section of the outer cape for its continued sediment supply. The Nauset Spit system consists of three major parts: Nauset Spits--Eastham and Orleans, North Beach, and Monomoy Island.

Methods. Various techniques were used to provide insight into the dynamics of a northeast barrier beach system. A range of information collected during different time frames was examined to evaluate the role of overwash and foredune processes in barrier beach dynamics. Overwash processes were described from field data collected during several minor storms and during a major northeaster in February 1978. The response of vegetation to overwash burial and the colonization of washovers by vegetation were studied using data collected between 1977 and 1979. Transects were established along Nauset Spit to determine the development of plant communities and morphological features on barrier environments that have a well-documented history. Aerial

photographs and US Coast Survey maps were used to determine the changes in shoreline position and major barrier environments during the past 122 years. Earlier charts, maps, and accounts expanded these data back to the early 1600s, in a qualitative sense. Finally, cores and radiocarbon peat dates were used to define the geologic evolution of the barrier system.

Overwash and Aeolian transport. During storms, the convex beach profile is planed off by waves, while a large storm bar is constructed a short distance offshore. At high tide, swash may impinge directly on the seaward face of barrier dunes. Low-profile areas, created by blowouts or vehicles, allow swash penetration as overwash through the dune line. Overwash is defined as the transport of seawater and associated sediment or drift from the beach face to the back barrier.

The most severe storm to affect Nauset during the study period was the 1978 northeaster. The February 1978 northeaster may have been the most significant extratropical storm to strike the Cape Cod shoreline in the last 50 to 100 years. This storm was estimated to have a deepwater wave height of 5 meters (m) and a probable return interval of 75 years. Nearshore breaker heights approached 3 m and storm surge was approximately 1.2 m. During the storm, current meter measurements recorded maximum instantaneous velocities of overwash surges up to 2.44 m/sec. These surges were erosional and removed most of the vegetation. As the overwash surges proceeded toward the inland dune, they declined in velocity and became principally depositional at this point. Large quantities of sediment were transported across the berm by overwash surges and deposited in washover fans and flats. Volumetric determinations showed that as much as 400 m^3/m of overwash sand was transported landward during this event, with penetration distances of 250 m bayward of the dune line and deposition thicknesses up to 1.65 m above the living salt marshes on the landward portions of the barrier.

Although a substantial amount of sand is deposited during storm events, much of this sediment is redistributed during interstorm periods. Tidal currents reworked the sand along fan margins, but in other areas wind has been the principal means of redistributing the sediment. Prevailing northwest and southwest offshore winds during the winter often exceed 30 knots per hour and frequently average 10 to 15 knots per hour. Since this wind field is generated by Canadian high-pressure cells, strong winds are accompanied by clear weather, resulting in maximum transport because the sand is dry. The

redistribution of deposited sand associated with one large overwash fan was observed over an 18-month period following the 1978 storm. Approximately 8,000 m^3 of sand was deposited during the storm. Nearly 3,000 m^3 of this deposit was deflated during the following 18 months. About 50 percent of this material was incorporated into dunes adjacent to the overwash, and about 50 percent was returned to the ocean beach.

Vegetative response to overwash. Dunes that are eroded during overwash are recolonized by dune vegetation by means of seeds and plant fragments regenerating in drift piles found on washover deposits and by rhizome extension from nearby remnant dunes. Living plant material torn from the dunes is, in many cases, able to regenerate. All four major dune species on Nauset Spit-Eastham (*Ammophila breviligulata, Solidago sempervirens, Lathyrus japonicus*, and *Artemisia stelleriana*) can reproduce vegetatively from plant fragments. The February 1978 storm destroyed large sections of dune line, uprooting vast quantities of organic material. In 1978, seven species of flowering plants regenerated from fragments. The four above-named species also exhibited both vertical and lateral rhizome extension. Seedlings were seldom found in drift piles in areas that had been dunes, because overwash surges carried light material through the area toward the fan terminus.

The major dune species are very tolerant of sand burial by overwash. *Ammophila breviligulata* is able to recover from 59 centimeters (cm) of overwash burial, and its physiological limit for recovery was probably not reached in this study. *Ammophila* recovered from artificial burial to a depth of more than 1 m. The season that overwash occurs may play an important role in the dune community response to burial. Young dune plants or dune plants that have recently broken dormancy have tissue that is susceptible to damage from saltwater exposure. Older plants are better able to withstand contact with saltwater.

Though dune communities may be either eroded or buried by overwash events, the salt-marsh communities are generally subject only to burial. Salt-marsh vegetation on Nauset Spit-Eastham did not grow through washover deposits greater than 33 cm deep. In areas where deposition was from 22 to 33 cm, only *Spartina patens* and *Spartina alterniflora*, the major plant species in the high and low marsh communities, respectively, were able to recover. *Spartina patens* cover and density were reduced when buried to a depth of 33 cm. Cover and density of *Spartina alterniflora* were not reduced

in areas receiving shallow burial. However, *Spartina alterniflora* was not able to recover from overwash burial in excess of 22 cm.

Recovery of plant communities following overwash is related to the plant community type and the frequency of overwash events. Dunes have been evident from aerial photography analysis on washovers deposited over salt marshes in as little as 3 years. Salt marshes may develop rapidly; however, marsh development is not as predictable as dune development. In as little as 10 years, salt marshes have become visible on aerial photos in areas that had been washovers. Only with shallow deposits at the outer edges of washovers do salt-marsh species recover from burial. These recovering species often do not survive unless overwash activity is reduced in the area.

Barrier evolution. Many barrier beaches along the east coast of the United States are undergoing landward retreat in response to sea-level rise. Landward displacement can be divided into two separate phenomena: migration of the barrier landform as a whole, and migration of physiographic features (e.g., sand dunes) on the barrier surface. Barrier migration occurs over long periods of time and is often the result of continuous shoreline erosion with periodic back-barrier extension resulting from inlet activity or overwash. There are three general mechanisms by which barrier beaches move landward: (a) aeolian, (b) overwash, and (c) inlet processes. All three of these mechanisms play a role in the evolution of the Nauset Spit barrier system.

Wind transport of sediment (aeolian transport) plays only a minor role in the landward migration of Nauset Spit because the net movement of windblown sand is in the seaward direction. However, as noted earlier, a portion of the sand deflated from overwash fans is incorporated into the landward margins of the dunes adjacent to the fan. This is one mechanism by which dunes are translocated landward.

Inlets historically have played a major role in landward sediment transfers along all sectors of the Nauset system and presently in many areas. Nauset Bay is essentially filled with marsh islands constructed on flood-tidal delta deposits. The upper reaches of Pleasant Bay have undergone extensive sedimentation and, hence, shallowing by inlet activity. The earliest records date to 1602 when explorers noted a series of inlets cut through the North Beach barrier. This spit segment has undergone at least three different series of inlet formation with subsequent inlet migration

downdrift. In this process of cyclic inlet breaching and spit regeneration, the entire barrier structure has been effectively displaced landward.

Overwash processes have proven to be of equal importance to the migration of the Nauset system. On Nauset Spit-Eastham, a salt marsh existed behind barrier dunes approximately 815 years before the present marsh. This marsh was subsequently buried with overwash sand that was carried up to 250 m beyond the bayward edge of the marsh. Sediment deposited along the bay shoreline was colonized by salt-marsh vegetation, and sand subsequently placed on top of the salt marsh was colonized by dune vegetation. On North Beach, core data revealed that washover sand had buried a salt marsh approximately 200 years ago; peaty material was outcropping along the ocean beach in 1978. Salt-marsh vegetation had colonized this washover surface and survived long enough to form a peat layer before being buried by overwash again. Therefore, "barrier rollover" at this location has been determined to be less than 250 years and was accomplished by overwash processes.

Barrier migration. Large-scale washovers play an important role in barrier migration. Prior to overwash, the barrier beach may consist of a continuous dune line backed by salt marsh. During a major storm, the barrier dune is eroded to a point where low-elevation dunes and blowouts are overtopped by overwash surges. These surges erode an increasingly wide channel through the dune line by lateral cutting until broad sections of the dunes are entirely flattened. During overwash, large volumes of sand may be carried from the beach and dune to the back barrier. Some of this sediment may be transported into the bay, resulting in landward extension of the barrier unit.

Following overwash, organic debris is left on the washover surface in large clumps. Drift lines are also deposited along the outer margins of washover flats by spring high tides and overwash surge. The washover surface is generally increased to elevations above the natural range of salt-marsh species. Therefore, fragments of dune plants present in drift lines regenerate and seeds germinate, leading to the establishment of dune vegetation. Rhizome extension from surrounding dunes plays a smaller role in the stabilization and revegetation of large washovers than it does on smaller fans due to the large ratio of fan area to vegetative perimeter.

Dunes develop in the location of drift material and continue to build as overwash continues to add sediment to the back of the washover in upwind

positions relative to the drift lines. The lack of constraining foredunes allows overwash to take place for several years (5 to 10), augmenting this sand supply. Drift-line dunes are usually not eroded during overwash since they are located in landward positions. During the final stages of dune recovery, washover passages through the foredunes periodically coalesce during windy, interstorm periods.

Eventually, the dune line becomes continuous and the back barrier deflates the intertidal elevations at which moist sand will not saltate (bounce along by the impact of dislodged sand grains). The net result of large-scale overwash is that after many years (10 to 20), all barrier features are displaced landward. New dunes, resulting from sand accumulation around vegetation initiated in drift lines, coalesce with vegetation expanding by rhizome extension from remnant dunes. New salt marsh forms in the lee of these dunes, and the barrier beach as a whole is displaced landward with the establishment of the same general physiographic features and vegetative composition.

Engineering implications. All sections of the Nauset Spit system are subject to dramatic changes either by inlet activity or overwash. Southern portions of the Nauset Spit system are eroding more rapidly than the northern portions, which are nearer to the glacial cliffs, the major source of sediment along Outer Cape Cod. Increased erosion rates lead to more rapid landward migration and more unstable conditions. The outer shoreline appears to be readjusting toward a slightly more southwest to northeast orientation. Due to this shoreline movement, man-made structures along all sections of the spit system will be subject to destruction during storms. The most stable unit, Nauset Spit-Eastham, appears to be undergoing a longer migration cycle than other sections of the spit system.

Artificial creation and maintenance of dunes and salt marshes can be used to extend various periods of the migration cycle but will not alter the basic biogeological process. Extensive dune stabilization can reduce overwash activity for a period of time, resulting in calm back-barrier conditions necessary for the establishment of salt-marsh vegetation. However, artificially established dunes will continue to narrow in the absence of washover sediment in upwind positions, and these foredunes will eventually be eroded.

PREFACE

This report was sponsored by the Office, Chief of Engineers (OCE), US Army, as a part of the Environmental Impact Research Program (EIRP) Work Unit 31533 entitled Foredune Ecology, which was assigned to the US Army Coastal Engineering Research Center (CERC). The Center, originally located at Fort Belvoir, Va., moved to the US Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., on 1 July 1983. The Technical Monitors for the study were Dr. John Bushman and Mr. Earl Eiker of OCE and Mr. Dave Mathis, Water Resources Support Center.

The report was prepared by Mr. Robert E. Zaremba of the Massachusetts Audubon Society and Mr. Stephen P. Leatherman, University of Massachusetts, under a cooperative agreement between CERC and the US National Park Service. Mr. P. L. Knutson of CERC prepared the Summary.

Mr. Knutson was the CERC Technical Advisor for the contract, under the general supervision of Mr. E. J. Pullen, Chief, Coastal Ecology Branch, and Mr. R. P. Savage, Chief, Research Division, CERC. Dr. Roger T. Saucier, WES, was the Program Manager of EIRP.

Technical Director of CERC at Fort Belvoir during the study and preparation of this report was Dr. Robert W. Whalin. Commander and Director of WES during this period was COL Tilford C. Creel, CE; Technical Director was Mr. F. R. Brown.

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CONVERSION FACTORS, US CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
gallons (US liquid)	3.785412	cubic decimetres
knots (international)	0.5144444	metres per second
millibars	1.0197×10^{-3}	kilograms per square centimetres

OVERWASH PROCESSES AND FOREDUNE ECOLOGY, NAUSET SPIT, MASSACHUSETTS

by

Robert E. Zaremba

and

Stephen P. Leatherman

I. INTRODUCTION

1. Purpose and Scope.

Along the east coast of the United States, many barrier beaches are undergoing landward retreat as the sea level rises. Human development of these barriers has resulted in an increasing conflict between natural processes and artificial stabilization. Jetties, groins, and seawalls are being used to stabilize the shoreline with varying degrees of success. Artificially constructed dunes are being used successfully in many developed areas as barriers to the inland penetration of waves and storm surges (Knutson, 1980).

This research was undertaken to provide the scientific data necessary to understand the natural dynamics of a northeast barrier beach. Before widespread use can be made of stabilization techniques, it is necessary to evaluate the consequences of manipulation of barrier environments with relation to unalterable physical processes and the limits of biological systems.

Coastal research to date has focused on either ecological or geological processes; only a few projects have been designed to consider the interaction between vegetation and the physical factors which shape barrier beaches. This is the first detailed study undertaken to gather and analyze data on the effect of physical processes, principally overwash, on plant communities and physiographic features of barrier beaches in the northeast. Nauset Spit, Cape Cod, Massachusetts, was chosen for this investigation because overwash has frequently occurred along this retreating shoreline and historical information is available for the past 380 years.

2. Research Approach.

Various techniques were used to provide insight into the dynamics of a northeast barrier beach system. A range of information collected during different time frames was examined to evaluate the role of overwash and foredune processes in barrier beach dynamics. Overwash processes were described from field data collected during several minor storms and during a major northeaster in February 1978. The response of vegetation to overwash burial and the colonization of washovers were studied using data collected between 1977 and 1979. Vegetative-physiographic transects were constructed along Nauset Spit to document the development of plant communities and morphological features on barrier environments that have a well-documented history. Vertical aerial photography and U.S. Coast Survey maps were used to determine the changes in shoreline position and major barrier environments during the past 122 years. Earlier charts, maps, and accounts expanded these data back to the early 1600's, in a qualitative sense. Finally, cores and radiocarbon peat dates were used to define the geologic evolution of the barrier.

a. Overwash and Aeolian Processes. During several storms which resulted in overwash, measurements were taken of surge duration, velocity, flow depth, and bed scour. These data have important ecological implications since flow velocity and turbulence determine whether an overwash surge is depositional or erosional. From these measurements and from field surveys, the impact of an individual storm of a particular size on the barrier can be assessed. This information can also be used to determine the minimum distance from the berm crest for beach grass restabilization.

Elevation transects were surveyed before and after major storms to document the rate of beach and dune erosion and quantify the volume of sediment carried by overwash to the back barrier. As the resulting washovers deflated, elevation surveys were continued to determine the amount of sediment loss from these deposits. Sand lost from the barrier by wind deflation and trapped in vegetated dunes as a result of washovers was also measured.

b. Vegetative Response to Overwash. Vegetation at three sites on Nauset Spit was extensively sampled in 1977 before the major northeaster in February 1978. All three sites were buried by overwash sand during this storm and were resampled during the following two summers. Examples of all major plant communities on the Nauset Spit system are included in these data to assess the response of coastal vegetation to overwash burial.

During major overwashes large volumes of sand are deposited on salt marshes, killing plants. Following the 1978 northeaster, barren washovers covered large areas of the Nauset Spit system. The means and rate of revegetation of these washovers have been studied, using the vegetation sampling sites surveyed before the storm, with particular attention focused on the role of drift lines in the revegetation and in the development of new dunes.

c. Barrier Evolution. Shallow cores (up to 3 meters long) were used to determine the lateral and vertical extent of washover deposits and to provide information on the geologic rate and means of landward barrier migration. Maps, charts, and accounts dating back to the early 1600's were consulted to reconstruct historical shoreline changes. U.S. Coast Survey maps (1851, 1856, 1868, 1886) and vertical aerial photographs (1938 to 1978) were used to map shoreline changes and physiographic features. The distribution of washovers along the spit system was mapped from aerial imagery and located in the field. This information can be used to determine the rate of change in vegetation on washovers and on more stable parts of the barrier.

Vegetative-physiographic transects at 15 locations along the Nauset Spit system were established to document plant community development on washovers. These transects were also used to delineate topographic and plant species changes associated with the formation and stabilization of foredunes. The relationship between species composition and physical factors such as salt-spray exposure, saltwater flooding, sand burial, and elevation was delineated by these field studies.

3. Previous Studies.

Research on coastal vegetation has focused primarily on community zonation, in relation to environmental factors, and on sand dune and salt-marsh development. Detailed work has been conducted on the effects of salt

spray, water-table height, soil moisture, salinity, and nutrient availability on individual species and on community structure (Oosting and Billings, 1942; Boyce, 1954; Ranwell, 1958, 1959; Tansley, 1968; Art, 1976). The theory of community succession was first investigated on Lake Michigan sand dunes and has since been studied extensively on coastal dune communities (Cowles, 1899; Ranwell, 1975). Other, more applied research has concentrated on rates of dune building and on salt-marsh establishment (Woodhouse and Hanes, 1967; Redfield, 1972).

In recent years, overwash has been recognized as an important factor in the development of both the type of community on barrier beaches and the geomorphology of the barrier itself (Hosier, 1973; Godfrey and Godfrey, 1976; Hosier and Cleary, 1977). On southern and mid-Atlantic barriers, frequently occurring overwash has been studied in detail for both individual storms, using field observations and surveying techniques (Hosier, 1973; Leatherman, 1976; Travis, 1976), and long-term trends through coring (Godfrey, 1970; Hosier, 1973) and aerial photographic analysis (Hosier and Cleary, 1977). Few studies have been conducted on northeast barrier beaches where overwash is an infrequent event. The geomorphology of a northeast barrier beach and the response of vegetation to overwash burial have been conceptually modeled (Godfrey, Leatherman, and Zaremba, 1979).

There have been a large number of geological studies pertaining to overwash with respect to barrier evolution. Although various theories have been proposed to explain landward migration of barrier beaches, most coastal researchers subscribe to the concept of continuous migration by shoreface retreat and overwash-aeolian-inlet dynamics (Dillon, 1970; Pierce, 1970; Kraft, 1971; Swift, 1975; Leatherman, 1976, 1979a; Armon, 1979; Fisher and Simpson, 1979). Extensive reviews of this literature are provided in annotated bibliographies by Leatherman and Joneja (1980) and Leatherman (1981).

Most researchers have found that inlets along the northeast coast are predominantly responsible for landward barrier migration. For instance, Armon (1979) reported that 90 percent of landward sediment transfers occur within inlet settings along the Malpeque barrier system in the Gulf of St. Lawrence, Canada. Overwash, however, plays an important role in association with aeolian and dune-building processes in the upward growth and development of a barrier (Fisher and Simpson, 1979; Leatherman, 1979b, 1979c). There have been few other studies of northeast barriers, and none of the studies have utilized a geobotanical approach.

Dune stabilization experiments have been undertaken along the U.S. barrier coastline from Massachusetts to Texas (Savage, 1963; Gage, 1970; Dahl, et al., 1975; Woodhouse, 1978). Woodhouse and Hanes (1967) and Woodhouse, Seneca, and Broome (1976) conducted significant studies along the Outer Banks of North Carolina where sand fences and dune grasses were used to trap and retain windblown sand. Knutson (1977) summarizes planting guidelines for dune creation and stabilization.

Experimental dune restoration and stabilization have been conducted at Nauset Spit (Knutson, 1980). Experimental plots were established in 1970 near Nauset Harbor to compare the performance of *Ammophila breviligulata* (American beachgrass) to sand fencing for dune building. Although sand fences initially captured sand more rapidly than planted grasses, both techniques were nearly equally successful once the *Ammophila breviligulata* became established. This study demonstrated that dunes can be effectively and quickly created and

stabilized by *Ammophila breviligulata* along the northeast coast. No adverse impacts of this stabilization were identified.

4. Site Description.

The Nauset Spit system developed from the deposition of material eroded from the glacial cliffs of Eastham and Wellfleet and transported southward by littoral currents. This barrier beach system, which consists of three spit segments and two islands, was formed by spit elongation over the past 5,000 to 7,000 years. The spit system has continued to evolve and has migrated landward, constantly reducing the overall dimensions of the enclosed bays. Nauset Spit is dependent on the eroding headland (glacial) section of the outer cape for its continued sediment supply. The shoreline position of the spit is generally controlled by the erosion rate of these glacial bluffs since a smooth contour of the outer cape has been maintained through time by wave and current processes.

The Nauset Spit system consists of three major parts: Nauset Spits--Eastham and Orleans, North Beach, and Monomoy Island (Fig. 1). These sections can be considered individually even though they have been historically connected. Nauset Spits (Eastham and Orleans) and North Beach, which front enclosed bays, are discussed in this study.

Nauset Spits--Eastham and Orleans (Fig. 2) protect Nauset Marsh and serve as the outer barrier for Nauset Harbor. The barrier consists of a double spit, divided by Nauset Inlet. Prior to 1946, the south spit, Nauset Spit-Orleans did not exist because Nauset Inlet was located against the glacial headlands at Nauset Heights. Since that time, however, the spit has rapidly grown northward with lateral inlet migration at the expense of Nauset Spit-Eastham. This trend is occurring despite the long-term southward direction of net littoral drift along this section of the Atlantic coast of Cape Cod.

Nauset Harbor, a 547-hectare tidal lagoon, is a complex system with large tidal hydraulic differences. The mean tidal range in the Atlantic Ocean opposite the inlet is 2.1 meters; it is 1.3 meters just inside the inlet, decreases to 0.7 meter at Nauset Bay (near the Nauset Coast Guard Station to the north), and increases to 1.4 meters at the southern extremity of Town Cove (U.S. Army Engineer Division, New England, 1969). Tidal currents through Nauset Inlet have been measured at 6.5 kilometers per hour by Woods Hole Oceanographic Institute scientists (D. Aubrey, personal communication, 1978), and the existing inlet is hazardous to general navigation. The outline of the large ebb tidal delta is clearly defined at low tide by breaking waves. The shoals and inlet position shift seasonally, with major changes occurring during coastal storms.

North Beach (Fig. 3) is a 13-kilometer-long barrier spit that fronts Pleasant Bay and Chatham Harbor (Fig. 1). This spit section has been historically breached by migrating inlets at least three times; the earliest recorded breach was marked by the sinking of the *Sparrow-Hawk* in 1626. The term North Beach is confusing since sections of the spit are actually located north of this segment. North Beach and South Beach were created when North Beach was breached by an inlet in 1846. Sediment starvation by the downdrift-migrating (southward) inlet resulted in rapid erosion of the south spit. This report describes the cyclic phenomenon of inlet breaching and spit regeneration (lengthening southward by littoral drift) and its pronounced effect on both plant communities and barrier stratigraphy.

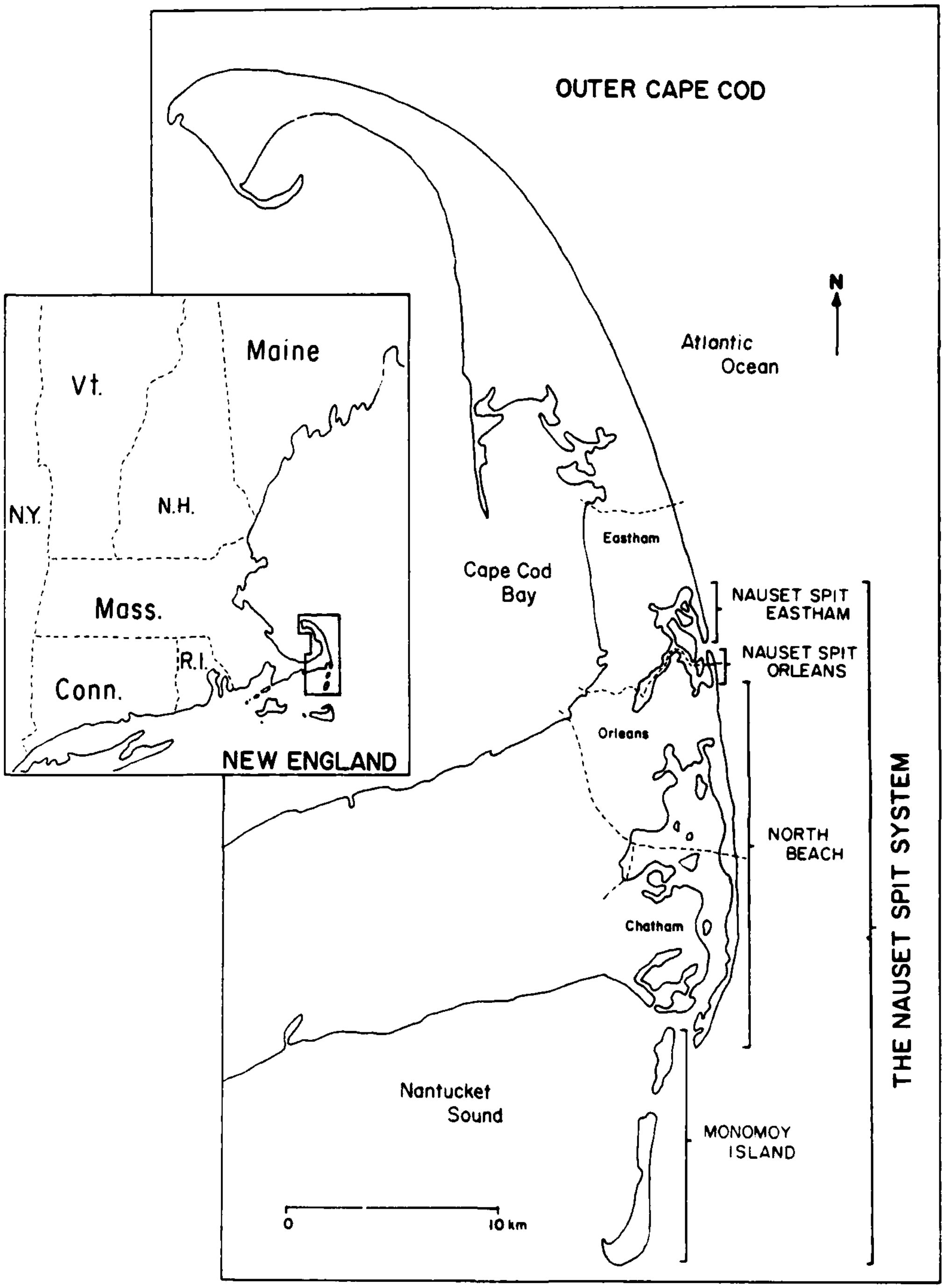


Figure 1. Map of Outer Cape Cod showing the Nauset Spit system.

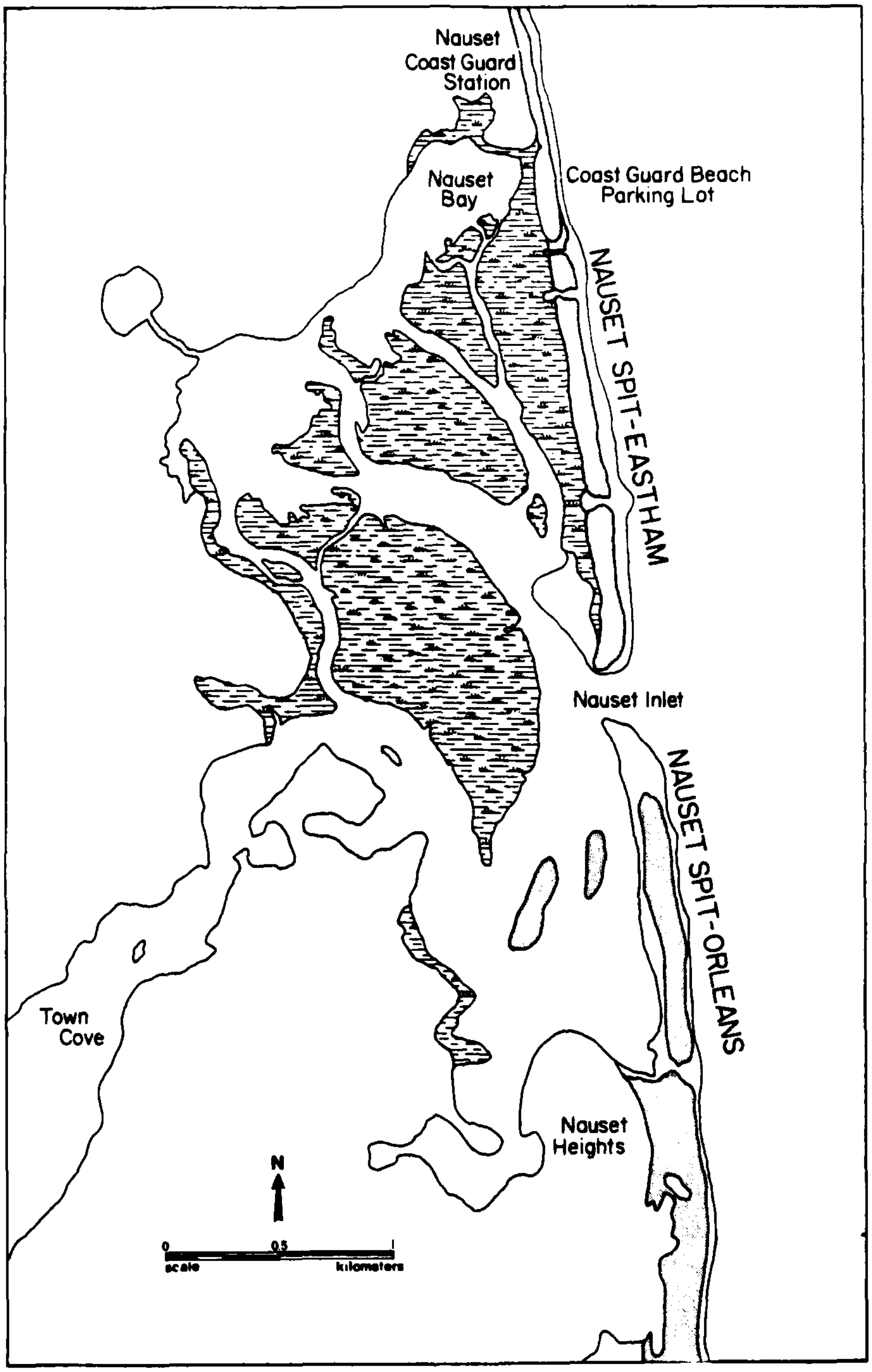


Figure 2. Map of Nauset Spits--Eastham and Orleans, 1977.

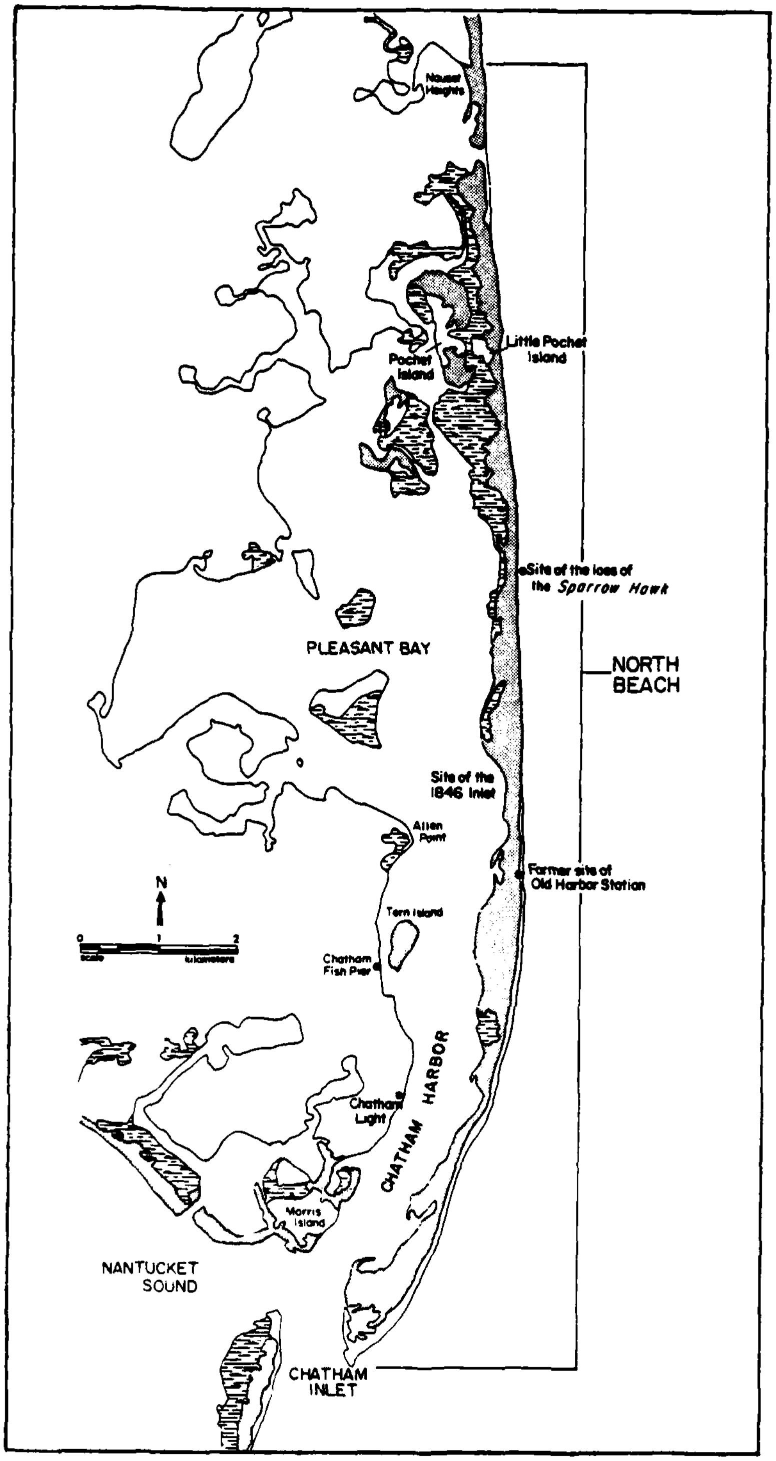


Figure 3. Map of the North Beach section of the Nauset Spit system.

The embayment protected by North Beach, which includes Pleasant Bay and Chatham Harbor, covers 2996 hectares at mean high water (MHW). Tidal ranges vary within the bay from 1.3 meters at Chatham Harbor entrance to 0.9 meter at Little Pleasant Bay. The mean tidal range in the Atlantic Ocean opposite Pleasant Bay is 2.0 meters, and 1.2 meters in Nantucket Sound (U.S. Army Engineer Division, New England, 1968).

The ocean front of Nauset Spit has eroded and migrated landward. Zeigler (1960) compared elevation transects surveyed from 1957 to 1959 to those ot Marindin (1889) and concluded that the rate of erosion is 1.2 to 1.8 meters (4 to 6 feet) per year where Nauset Spit is being driven into the marshes behind it. Overwash is the principal process transporting sediment across the barrier where backed by headlands or extensive salt marshes. Inlets, through the development of their extensive flood tidal deltas, have heen responsible for the large expanse of salt marsh in Nauset Harbor and upper Pleasant Bay.

Nauset Spit has always been of interest to coastal scientists because of its dynamic character. Mitchell (1873) and Marindin (1889) provide historical analyses of the spit, based on field surveys. Nickerson (1931) summarized their analyses and other historical accounts. More recent studies which enhance the knowledge and understanding of the barrier system include Ziegler, et al. (1964), Goldsmith (1972), Gatto (1975), Giese (1978), McClennen (1979), and the U. S. Army Engineer Division, New England (1979). Pertinent studies are discussed further in relationship to the results obtained from this research.

II. OVERWASH AND AEOLIAN TRANSPORT

1. Introduction.

Major studies of the overwash role in barrier beach dynamics have been conducted during the past two decades. Howard (1939) and Wilby, et al. (1939) provided detailed accounts of the effects of the 1938 hurricane on the south shore of the Long Island barriers, based solely on poststorm observations. Hayes (1967) noted that overwash caused by hurricanes has played a major role in the infilling of Laguna Madre behind Padre Island, Texas. Washover deposits were subsequently reworked by the wind, which transported additional sediment landward. Pierce (1969) adopted the sediment budget approach to estimate the volume of net sediment transport and define relative roles of inlets, overwash, and aeolian processes in landward migration. He calculated the relative proportions as follows: 70 percent inlets, 15 percent overwash, and 15 percent aeolian transport. There have been many qualitative papers on the role of overwash in barrier beach dynamics (e.g., Andrews, 1966; Kraft, 1971; Godfrey and Godfrey, 1974).

The first researchers to collect field data during a major storm were Fisher, Leatherman, and Perry (1974). They used a hand-held current meter to measure the velocity of overwash surges at Assateague Island, Maryland. Prestorm and poststorm elevation profiles documented the amount of deposition and subsequent wind deflation of overwash sediments. Leatherman (1976) continued these studies. Storm tide and barrier elevation were found to be the most important parameters in determining the magnitude of overwash. It was determined from field surveys that overwash deposition was nearly equaled by aeolian deflation,resulting in minimal net change on the fan surface after

several northeasters. Washover fans or flats served as temporary reservoirs for sand returned to the beach by prevailing offshore winds. Wind deflation was minimized only in regions where the barrier was narrow or low enough to deposit overwash in the bay or near the water table. These results indicated that small-scale overwashes do not play a significant role in the landward migration of Assateague Island. Sediment from minor overwashes is rapidly transported offshore by winds. Inlets are regarded as the primary means of barrier migration within a geologic time frame (Fisher and Stauble, 1977; Leatherman, Williams, and Fisher, 1977).

Armon (1975, 1979) showed that more than 90 percent of landward sediment transfers on the Malpeque barrier system were associated with the presence of inlets. Overwash and aeolian processes were important in the development of dunes. Rosen (1979), who also worked in the Canadian barriers of the Gulf of St. Lawrence, found that aeolian reworking of sand on washovers is an important factor in dune building. Therefore, the vertical accretion of barrier islands is largely governed by the interaction of overwash-aeolian processes and plant communities. This result correlates with Leatherman's (1979b) results at Assateague Island.

2. Overwash Hydraulics.

a. Introduction. During storms, the convex beach profile is planed off by waves, while a large storm bar is constructed a short distance offshore. At high tide, swash may impinge directly on the seaward face of barrier dunes. Low profile areas, created by blowouts or vehicles, allow swash penetration as overwash through the dune line. Overwash is defined as the transport of seawater and associated sediment or drift from the beach face to the back barrier. As overwash surges cross the dune line, additional sediment is eroded from the throat section, transported landward, and deposited in a fan shape to the lee of the dunes (Fig. 4). The extent of the erosional zone depends on flow conditions, which are a function of storm intensity. During a severe coastal storm, large sections of the barrier dune may be overtopped and flattened, forming extensive washover flats.

The throat is that section of a washover through the dune line. Constriction of waterflow in the throat often results in erosion. Once the overwash surges traverse this area, the flow is allowed to diverge due to the lack of horizontal constraints and the typical fanlike feature is created on the back barrier. Surge velocities are reduced due to flow divergence, frictional effects, and percolation losses, and the flow is generally depositional in nature. During overwash, the bay waters are superelevated with the storm tide. Where overwash surges pass into ponded water, velocities decrease quickly and sand is deposited rapidly, often resulting in steeply dipping delta foreset beds at the fan terminus.

b. Methodology. During the winter, weather was monitored continuously to predict possible coastal storms. Storm path and morphology of large northeasters capable of producing overwash at existing dune breaches on Nauset Spit were closely observed. Storms were usually detected early enough for the field team to reach the study site, set up the necessary instrumentation, and conduct a preoverwash survey.

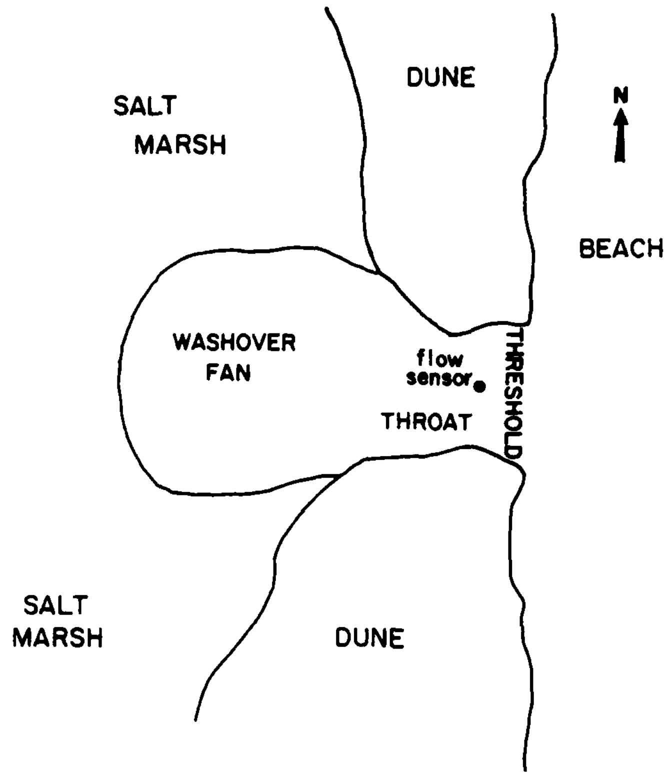


Figure 4. Location of flow sensor for overwash hydraulics measurements.

At Nauset Spit-Eastham, an attempt was made to quantify the hydraulic characteristics of overwash surges during storm conditions. A Marsh-McBirney electromagnetic current meter measured surge velocities. A current meter probe was placed in the throat of the washover landward of the barrier threshold (Fig. 4). An aluminum frame held the probe so that it intercepted an undisturbed flow (Fig. 5). A Weathermeasure strip-chart recorder, located within the protective cover of a truck, recorded the hydraulics of the event. Table 1 lists the storms that produced overwash at Nauset Spit between January 1976 and January 1980. Five of these storms were monitored during this period (Table 1).

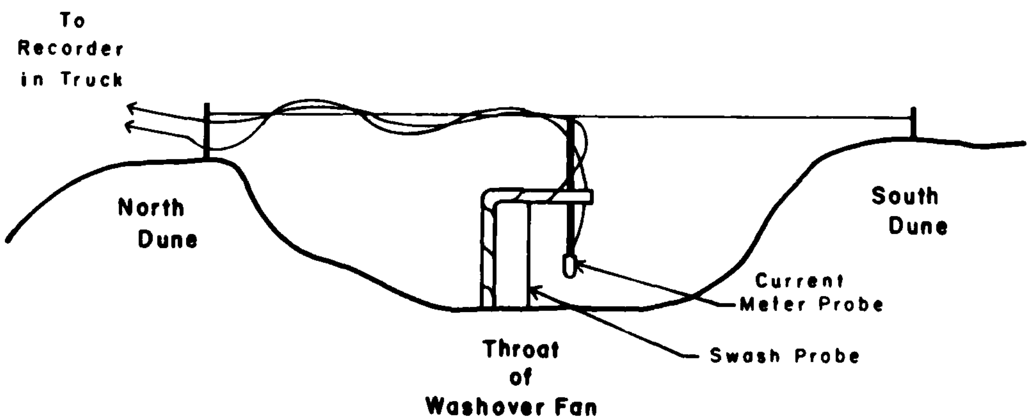


Figure 5. Instrument setup during an overwash.

Table 1. Dates of overwash events at Nauset Spit-Eastham between January 1976 and January 1980.

9 Feb. 1976[1]	10 May 1977[1]	25 Jan. 1979
10 Mar. 1976[1]	10 June 1977	28 to 29 Jan. 1979
16 Mar. 1976[2]	18 Nov. 1977	11 Aug. 1979
2 Sept. 1976	9 Jan. 1978	
12 to 13 Nov. 1976	6 to 7 Feb. 1978[2]	

[1]Event observed (monitored).

[2]Event recorded (monitored).

c. Analysis of Data.

(1) Small-Scale Events. The first observed overwash occurred as discrete pulses of water during the 5:56 a.m. high tide on 9 February 1976. Commencing at 5:00 a.m. and continuing for 2 hours, flow depths were generally less than 15 centimeters. The average wind velocity was 30 knots from the northeast, which resulted in blowing snow and large drifts. Measurements were not attempted during this threshold event.

The storm center of the 10 March 1976 northeaster passed approximately 370 kilometers offshore of Cape Cod. The central pressure was 992 millibars, and 40-knot winds were recorded at the offshore weather station "Hotel." Approximately 25 overwash surges were observed during the 2-hour period bracketing the 5:50 a.m. high tide. Surge depths were only 5 to 10 centimeters so current meter readings were not possible. This northeaster also represented the threshold conditions necessary for an overwash at preexisting dune breaches.

The third overwash on 16 March 1976 was monitored at the first breach in the dunes south of Orleans parking lot on North Beach (Fig. 3). Nearshore, 2-meter waves approached from the east, and northeast winds averaged 30 knots. The storm, which had a central pressure of 968 millibars, tracked less than 37 kilometers eastward of Cape Cod, producing a high storm surge. During a 2-hour interval (10:55 to 12:54 p.m.) bracketing the 11:30 p.m. high tide, more than 200 surges were recorded for an average of 1.6 surges per minute. Average flow depth was 15 centimeters with a maximum of 25 centimeters.

The velocity probe of the electromagnetic current meter was located 5 centimeters above the bed surface and was periodically adjusted during overwash to maintain a constant height as the sand surface eroded and accreted. The initial response of the dry probe to surging water resulted in a velocity spike on the recorder. Since this velocity maximum was only apparent and not real (D. Aubrey, personal communication, 1980), the curve was smoothed by filtering out this instantaneous response.

Table 2 lists the surges, time of occurrence, and maximum velocity for the 16 March 1976 overwash. The highest velocity surges occurred within 30 minutes of the predicted high tide (11:30 p.m.), but overwash continued for another 1.5 hours. Although the highest instantaneous velocity recorded was

Table 2. Overwash surge measurements taken on 16 March 1976.

Surge No.	Time (hr:min:s)	Max. velocity (m/s)	Surge No.	Time (hr:min:s)	Max. velocity (m/s)	Surge No.	Time (hr:min:s)	Max. velocity (m/s)
1	10:55:15	1.53	71	11:45:26	1.53	141	12:16:13	1.22
2	10:56:12	1.75	72	11:45:40	0.92	142	12:16:46	1.14
3	10:57:24	0.76	73	11:46:05	0.84	143	12:17:18	0.37
4	10:58:50	1.68	74	11:46:20	1.91	144	12:17:38	0.30
5	11:00:20	0.30	75	11:47:05	0.84	145	12:18:00	2.14
6	11:01:40	1.75	76	11:47:50	0.30	146	12:18:26	0.84
7	11:02:20	1.22	77	11:48:35	2.14	147	12:18:50	0.15
8	11:03:30	0.99	78	11:49:36	1.45	148	12:19:10	0.15
9	11:04:46	2.44	79	11:50:10	1.07	149	12:19:18	0.37
10	11:05:05	1.07	80	11:50:22	0.69	150	12:19:26	0.52
11	11:05:24	0.61	81	11:50:40	0.84	151	12:19:40	0.45
12	11:05:50	2.29	82	11:51:10	1.83	152	12:19:52	2.21
13	11:06:30	0.76	83	11:51:50	0.37	153	12:20:12	0.22
14	11:07:15	0.76	84	11:52:13	1.83	154	12:20:28	0.15
15	11:07:55	0.84	85	11:52:32	2.21	155	12:20:46	0.76
16	11:08:15	0.30	86	11:53:13	0.76	156	12:20:56	0.45
17	11:08:40	0.84	87	11:53:30	0.15	157	12:21:38	0.76
18	11:09:10	0.45	88	11:53:40	0.30	158	12:21:55	0.92
19	11:09:40	0.30	89	11:53:55	1.68	159	12:22:46	0.45
20	11:12:34	1.37	90	11:54:12	0.30	160	12:23:35	0.30
21	11:13:15	0.52	91	11:54:30	0.30	161	12:23:42	0.15
22	11:13:48	0.30	92	11:54:50	0.76	162	12:23:58	0.15
23	11:14:40	0.92	93	11:55:05	0.30	163	12:24:05	0.15
24	11:15:25	1.14	94	11:55:16	2.06	164	12:24:10	0.15
25	11:16:02	2.29	95	11:55:50	2.14	165	12:24:16	0.22
26	11:16:25	0.45	96	11:56:10	1.37	166	12:24:32	0.22
27	11:16:50	0.45	97	11:56:34	1.68	167	12:24:46	0.01
28	11:17:50	0.15	98	11:56:52	0.30	168	12:24:52	0.01
29	11:18:15	0.15	99	11:57:12	0.45	169	12:25:15	0.45
30	11:18:50	0.22	100	11:57:35	0.52	170	12:25:28	0.22
31	11:19:20	1.30	101	11:57:56	0.15	171	12:25:40	0.45
32	11:19:50	0.30	102	11:58:14	0.15	172	12:25:54	0.15
33	11:20:55	2.29	103	11:58:20	1.53	173	12:26:10	0.52
34	11:21:30	1.53	104	11:58:42	1.30	174	12:26:54	0.01
35	11:23:02	0.15	105	11:58:55	0.92	175	12:27:11	0.22
36	11:22:15	0.03	106	11:59:40	0.84	176	12:28:00	1.45
37	11:22:30	0.03	107	11:59:52	1.53	177	12:28:06	1.98
38	11:23:00	0.99	108	12:00:26	0.30	178	12:28:26	0.15
39	11:23:36	1.37	109	12:01:12	1.68	179	12:28:32	0.30
40	11:24:50	0.30	110	12:01:30	1.45	180	12:28:43	0.15
41	11:25:50	1.53	111	12:02:00	0.15	181	12:29:04	0.15
42	11:26:30	1.14	112	12:02:10	0.15	182	12:29:14	0.15
43	11:27:40	1.14	113	12:02:20	0.15	183	12:30:52	0.01
44	11:28:20	0.76	114	12:02:42	0.15	184	12:31:04	0.01
45	11:29:30	1.14	115	12:03:20	1.30	185	12:31:34	0.01
46	11:30:30	1.14	116	12:04:42	1.22	186	12:31:54	0.15
47	11:31:12	1.45	117	12:05:24	1.53	187	12:32:00	0.15
48	11:31:55	1.14		12:06:05	1.53	188	12:32:23	0.15
49	11:32:25	0.45	119	12:06:49	1.45	189	12:32:38	0.30
50	11:32:50	0.61	120	12:07:23	0.15	190	12:32:52	0.30
51	11:33:12	0.61	121	12:07:50	0.22	191	12:33:00	1.45
52	11:33:40	0.30	122	12:08:59	1.45	192	12:33:18	0.15
53	11:34:40	0.76	123	12:09:20	1.53	193	12:33:40	1.53
54	11:35:10	0.30	124	12:09:30	0.69	194	12:33:54	0.69
55	11:35:24	0.15	125	12:09:46	1.22	195	12:34:05	0.15
56	11:35:35	0.52	126	12:09:58	0.15	196	12:35:14	1.53
57	11:36:30	0.30	127	12:10:28	1.22	197	12:35:58	1.91
58	11:37:05	0.61	128	12:10:45	0.99	198	12:36:30	0.22
59	11:37:30	1.30	129	12:10:55	0.69	199	12:36:42	0.30
60	11:38:05	1.07	130	12:11:10	0.76	200	12:37:18	0.15
61	11:38:24	1.22	131	12:11:32	0.92	201	12:38:30	0.22
62	11:39:15	1.30	132	12:12:08	0.76	202	12:39:40	0.30
63	11:39:40	1.53	133	12:12:30	0.76	203	12:49:15	0.92
64	11:40:25	0.69	134	12:12:46	0.45	204	12:49:40	0.30
65	11:41:25	1.14	135	12:13:04	0.45	205	12:50:02	0.30
66	11:42:06	0.61	136	12:13:38	0.01	206	12:50:16	0.15
67	11:42:40	1.45	137	12:13:58	0.30	207	12:51:28	0.15
68	11:43:06	1.53	138	12:14:37	0.92	208	12:52:22	0.37
69	11:44:05	0.45	139	12:15:30	0.99	209	12:54:18	0.37
70	11:44:36	0.45	140	12:15:58	0.69			

2.44 meters per second, average velocity for the 75 largest surges was only 1.4 meters per second. Overwash surges in rapid succession often had high velocities and large flow depths; percolation losses were minimal. A double surge appears in Figure 6. Highest velocities and greatest flow depths were associated with the turbulent head of the overwash bore. A long tail of low velocities and low flow depths was recorded as the surge passed the current meter probe (Fig. 6).

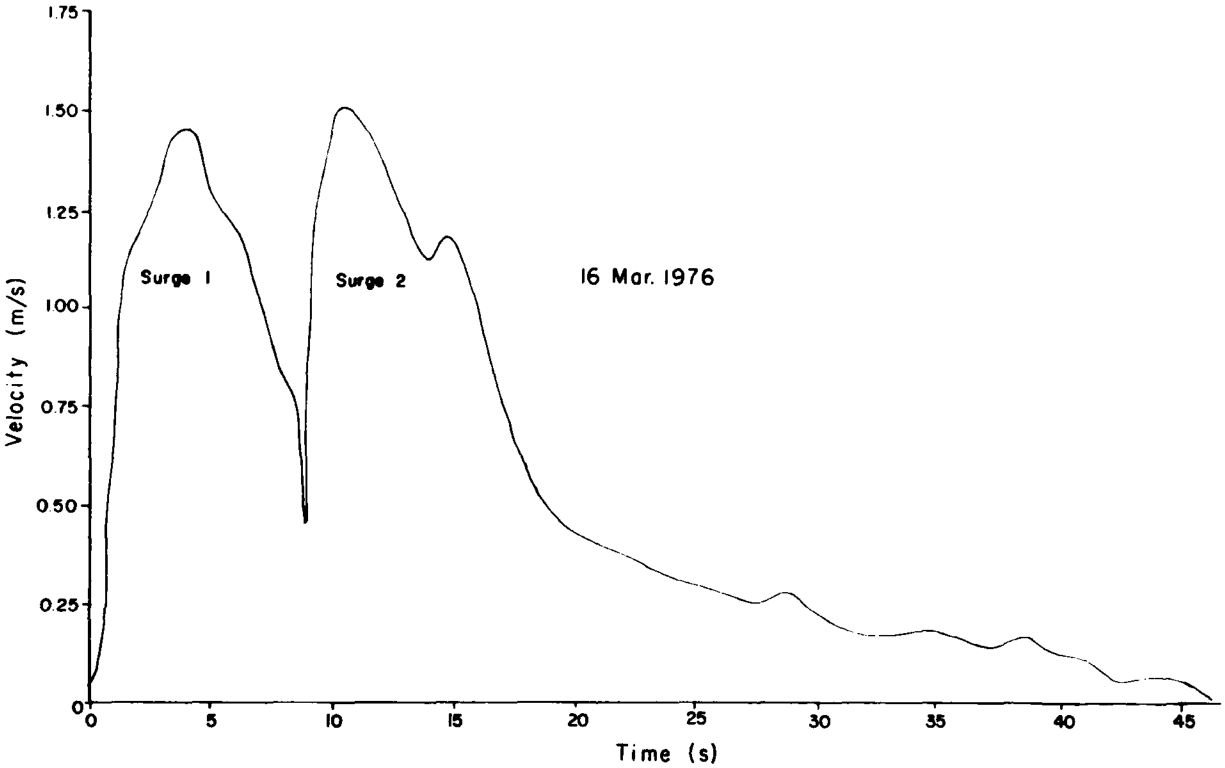


Figure 6. Overwash surge velocities recorded during the 16 March 1976 northeaster.

It is interesting to compare in a qualitative manner the beach response north and south of Nauset Inlet during the 16 March 1976 storm. At North Beach the berm was displaced 1.5 meters landward, but its integrity as a topographic feature was maintained. The beach was relatively wide and dune erosion was minimal. There were localized areas of more severe beach erosion which correlated with depressions (holes) in the nearshore bar system.

North of the inlet at Nauset Spit-Eastham, the berm was removed as the convex beach profile was flattened. The dunes were vertically scarped on the seaward face, and there was a concentrated surface layer of heavy minerals at the toe of the eroding dune. At washover flats just north of Nauset Inlet, small, incipient dunes were completely eliminated. Larger, more extensive dunes were severely eroded, and the inlet channel appeared to be widened and displaced northward. Nauset Spit-Eastham eroded much more than North Beach during this storm.

During the first week of September 1976, a distant tropical storm created a new breach in the dune line, just south (approximately 300 meters) of Nauset Coast Guard Beach parking lot. Large swells arrived during a spring high tide on a sunny, windless day, producing a breach at the position of a blowout and pedestrian-created path in the dune line. Water ponded on the backshore, draining marshward through the dune breach. A channel meandered through the dune line, and overwash sand was deposited on the adjacent marsh, creating a small washover fan. Very little of the living vegetation was displaced in the dunes since the throat crossed an old blowout; therefore, few living plant fragments were deposited with overwash sediments. Spring tides from the bay side did not reach the lip of the new washover fan; thus, no drift lines were deposited.

A small northeaster resulted in overwash during 12 and 13 November 1976, according to National Park Service rangers, adding an insignificant amount of sand to earlier washovers on Nauset Spit-Eastham. There were no significant overwashes recorded during the winter of 1977. Two small overwash events, 10 May and 10 June 1977, occurred in the spring. Although these events were sedimentologically insignificant, saltwater flooding during the growing season killed dune vegetation (see Sec. III).

On 9 January 1978 a northeaster passed to the west and north of Cape Cod, generating large waves in Cape Cod Bay and causing extensive flooding in Provincetown. During the final stages, the storm developed a southeast airflow along Outer Cape Cod, which resulted in overwash at spring high tide. Because of the peculiar storm path and morphology, overwash was not anticipated so no measurements were taken. This northeaster resulted in the formation of a new washover located only 100 meters south of the southern end of the Coast Guard Beach parking lot.

(2) Large-Scale Event. The 6 and 7 February 1978 northeaster may have been the most significant extratropical storm to strike the Cape Cod shoreline in the last 50 to 100 years. This northeaster affected the entire New England coastline. The National Park Service parking lot at Coast Guard Beach was destroyed, and property losses for several Massachusetts towns located on barrier beaches totaled about $200 million (Platt and McMullen, 1980). Using the Bretschneider technique (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977), this storm was hindcasted to have a significant deepwater wave height of 5 meters and a probable return interval of 75 years. Nearshore breaker heights approached 3 meters. Based on tide gage data (Boston, Massachusetts) and field surveys, the maximum storm surge was approximately 1.2 meters.

On 6 February 1978 an electromagnetic current meter was used to measure surge velocities during the first overwash-producing high tide (Fig. 7); 1 hour and 45 minutes of data (10:00 to 11:45 a.m.) was recorded on a strip chart. Instrumentation was set up at Nauset Spit-Eastham in the throat of the washover created by the January 1978 storm. Measurements during the height of the storm (10:20 p.m. high tide) and the following morning were not taken since access to the spit was impossible; the Coast Guard Beach parking lot was underwater and in the process of being destroyed (Fig. 8). Destruction of the parking lot also resulted in the generation of large quantities of rubble which would have damaged instruments if measurements had been attempted.

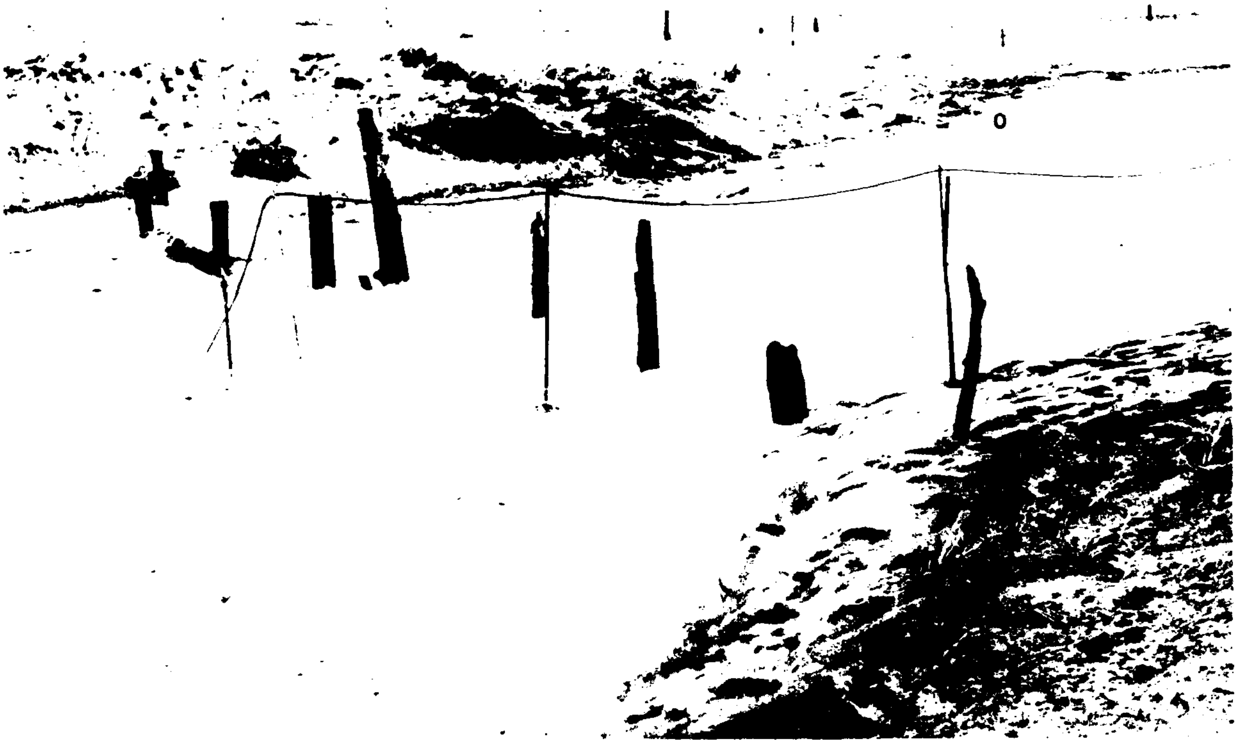


Figure 7. Frontal bore of overwash surge passing the flow sensors.

Figure 8. Coast Guard Beach parking lot and bathhouse facility destroyed 7 February 1978.

There were 127 surges during the 105-minute period for an average of 1.2 surges per minute (Table 3). Highest velocity surges were measured at the peak of high tide with velocities dropping to the range of 0.5 to 0.9 meter per second during the final 30 minutes of record.

Table 3. Overwash surge measurements of maximum instantaneous velocity for the 6 February 1978 northeaster recorded from 10:00 to 11:30 a.m.

Surge No.	Velocity (m/s)	Surge No.	Velocity (m/s)	Surge No.	Velocity (m/s)	Surge No.	Velocity (m/s)
1	0.61	33	1.37	65	1.68	97	0.30
2	1.14	34	2.29	66	1.37	98	0.92
3	1.83	35	1.07	67	0.76	99	0.92
4	1.53	36	2.14	68	0.84	100	0.84
5	1.60	37	0.92	69	1.68	101	0.45
6	2.06	38	0.61	70	1.53	102	0.61
7	1.45	39	1.07	71	1.98	103	1.53
8	1.83	40	1.53	72	1.68	104	0.84
9	0.84	41	2.14	73	0.61	105	1.22
10	0.53	42	1.45	74	2.14	106	0.92
11	1.14	43	1.22	75	1.07	107	0.61
12	2.29	44	2.44	76	0.76	108	0.52
13	2.29	45	1.53	77	1.30	109	0.76
14	1.45	46	1.07	78	1.22	110	0.52
15	1.68	47	1.14	79	2.29	111	0.45
16	1.75	48	1.83	80	0.76	112	1.22
17	1.83	49	1.83	81	1.22	113	1.07
18	0.92	50	1.22	82	2.21	114	0.37
19	0.53	51	1.68	83	0.61	115	0.45
20	0.61	52	1.14	84	1.22	116	0.84
21	1.14	53	1.30	85	1.91	117	0.52
22	1.60	54	1.53	86	1.60	118	0.92
23	1.68	55	0.92	87	2.06	119	0.45
24	0.92	56	1.75	88	0.61	120	0.52
25	1.83	57	1.22	89	0.61	121	0.45
26	1.83	58	1.53	90	0.92	122	0.52
27	1.60	59	0.61	91	1.30	123	1.07
28	0.84	60	1.45	92	1.98	124	0.45
29	0.92	61	1.37	93	0.92	125	0.45
30	1.53	62	1.68	94	1.53	126	0.61
31	2.14	63	1.22	95	0.30	127	0.61
32	1.45	64	1.14	96	0.30		

A part of the velocity record is shown in Figure 9. The record shows a continual curve, representing the surges of water passing the velocity probe. Between surges, the probe was partially wetted by rain, swash splash, and foam. This moisture, coupled with the high winds (+30 knots), resulted in an irregular response by the electromagnetic current meter and could easily be detected as noise.

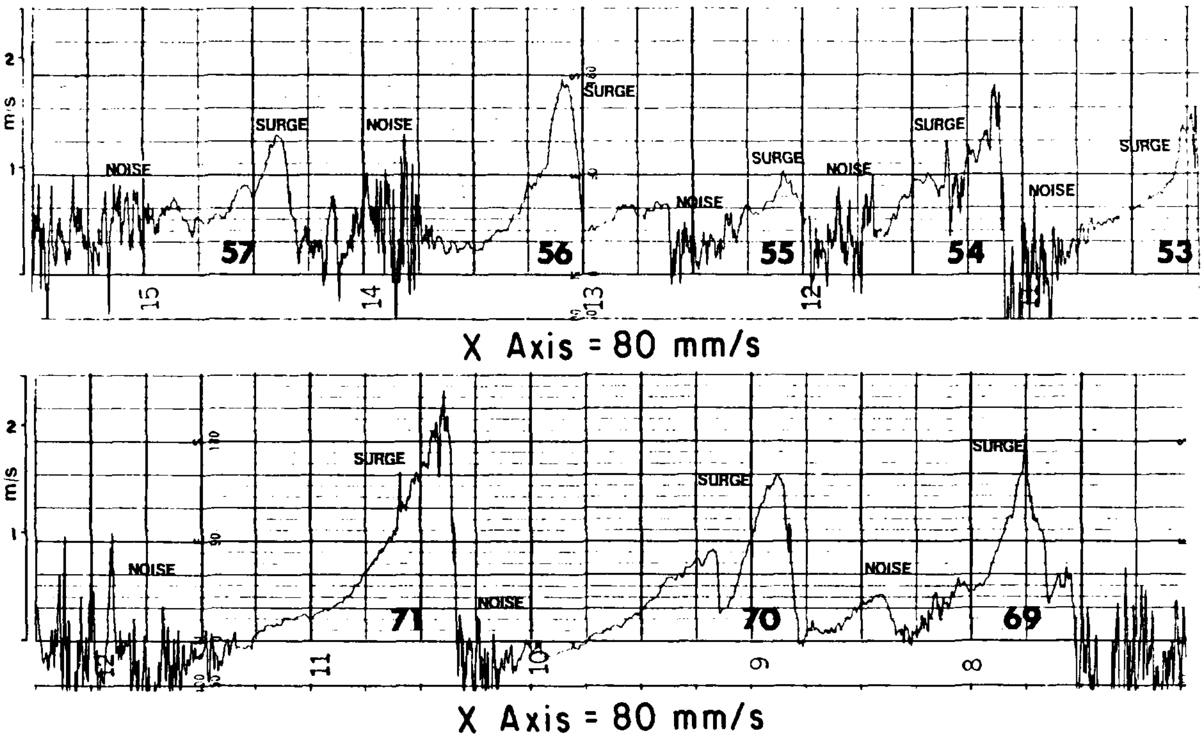


Figure 9. Strip-chart record of overwash surge velocities, 6 February 1978.

The horizontal axis of the chart represents the time scale, and the recorder speed was set at 80 millimeters per second during the overwash event. Figure 9 shows a series of high velocity surges (69 to 71) in rapid succession, followed by a short pause. There appears to be some periodicity to the record, which may be interpreted as a surf beat.

Flow depth measurements were not possible due to technical problems with the capacitance wire wave gage. From visual observations, it was evident that all surges were less than 0.5 meter deep; the average is generally less than 0.3 meter. Based on the relationship of low flow depths to high surge velocities, the frontal bore of the flow was supercritical as it passed through the washover throat (Leatherman, 1977, 1979d). These surges were erosional and removed most of the vegetation. As surges proceeded toward the fan, the velocity dropped due to the lack of horizontal constraints and percolation losses; the overwash surges were principally depositional at this point. This information helps to explain the pattern of vegetative changes during the event.

Because of its exposure to the Atlantic Ocean, Nauset Spit received the full force of the 2-day storm on 6 and 7 February 1978 (Fig. 10). Fortunately, the beach was surveyed just before the onset of the storm (5 February 1978) and soon after (9 February 1978). Figure 11 illustrates the magnitude of beach erosion resulting from this large-scale northeaster. The beach was in a winter (high energy) beach profile configuration before the February storm. As a result of the storm, the berm crest was pushed approximately 20 meters landward, with a loss of 30 cubic meters of sand per meter of beach. The dunes flanking site 1 washover on Nauset Spit-Eastham were eroded by an average of 9 meters. At North Beach, dune erosion was somewhat less with recession distances of 5 meters (Fig. 12). Entire sections of the dune line,

Figure 10. Major washover deposits on Nauset Spit-Eastham resulting from the February 1978 northeaster. The primary vegetation study area, site 1, is located south of large washover flats.

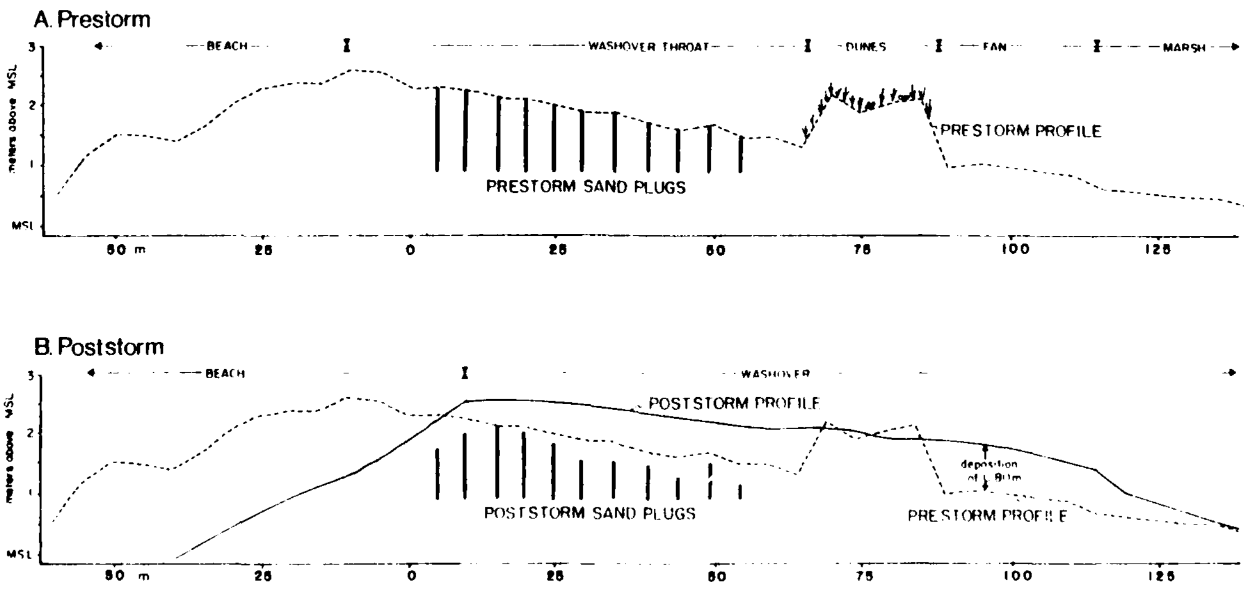


Figure 11. Elevation profile across site 1 before and after the February 1978 northeaster.

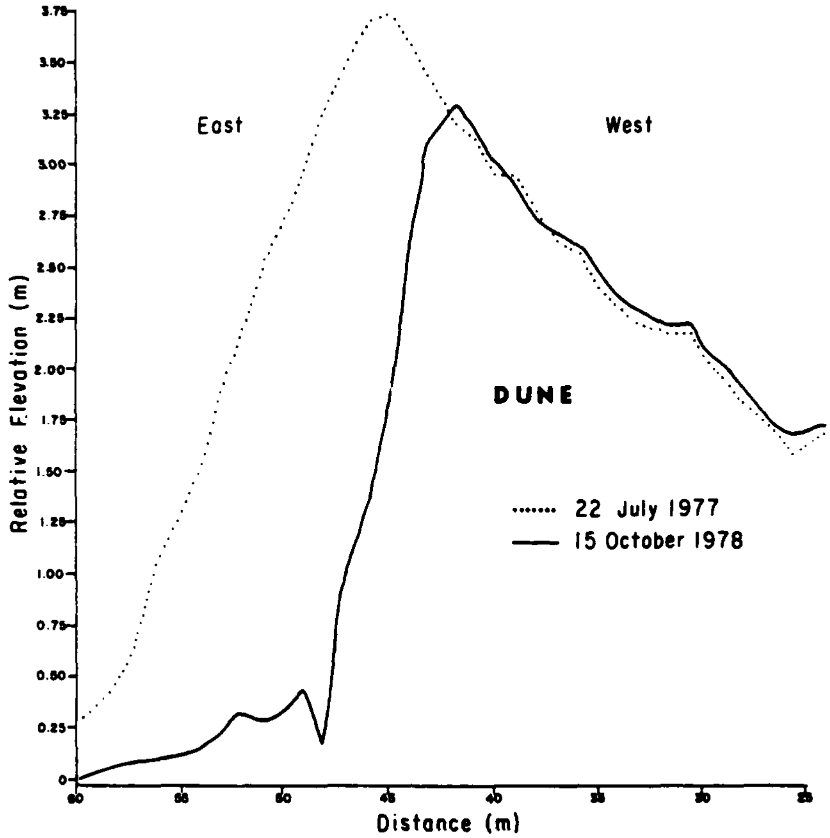


Figure 12. Barrier dune recession varied between 6 and 9 meters along Nauset Spit.

extending 300 to 500 meters along the beach, with dunes up to 6 meters high, were completely leveled in some areas. Large quantities of sediment were transported across the berm by overwash surges and deposited in washover fans and flats. Volumetric determinations showed that as much as 400 cubic meters per meter of overwash sand was transported landward during this event, with penetration distances of 250 meters bayward of the dune line and deposition thicknesses up to 1.65 meters above the living salt marsh.

3. Deposition.

a. Introduction. Three sites along Nauset Spit-Eastham were chosen for study in 1977 (Fig. 13). Site 1 is a small washover that was created by a northeaster in February 1972; this was the only washover on Nauset Spit-Eastham before 1976. Site 2, located approximately 300 meters south of the Coast Guard Beach parking lot, was created by a tropical storm in September 1976. The washover fan was placed above a living salt marsh, which provided the opportunity to monitor a washover from its inception. A third area, site 3, was chosen south of the former Outermost House site. The dunes in this area were low and narrow, and overwash was expected to occur with the next major storm (1977). Base-line data on preoverwash conditions were collected in 1977 at site 3 for comparison to poststorm data.

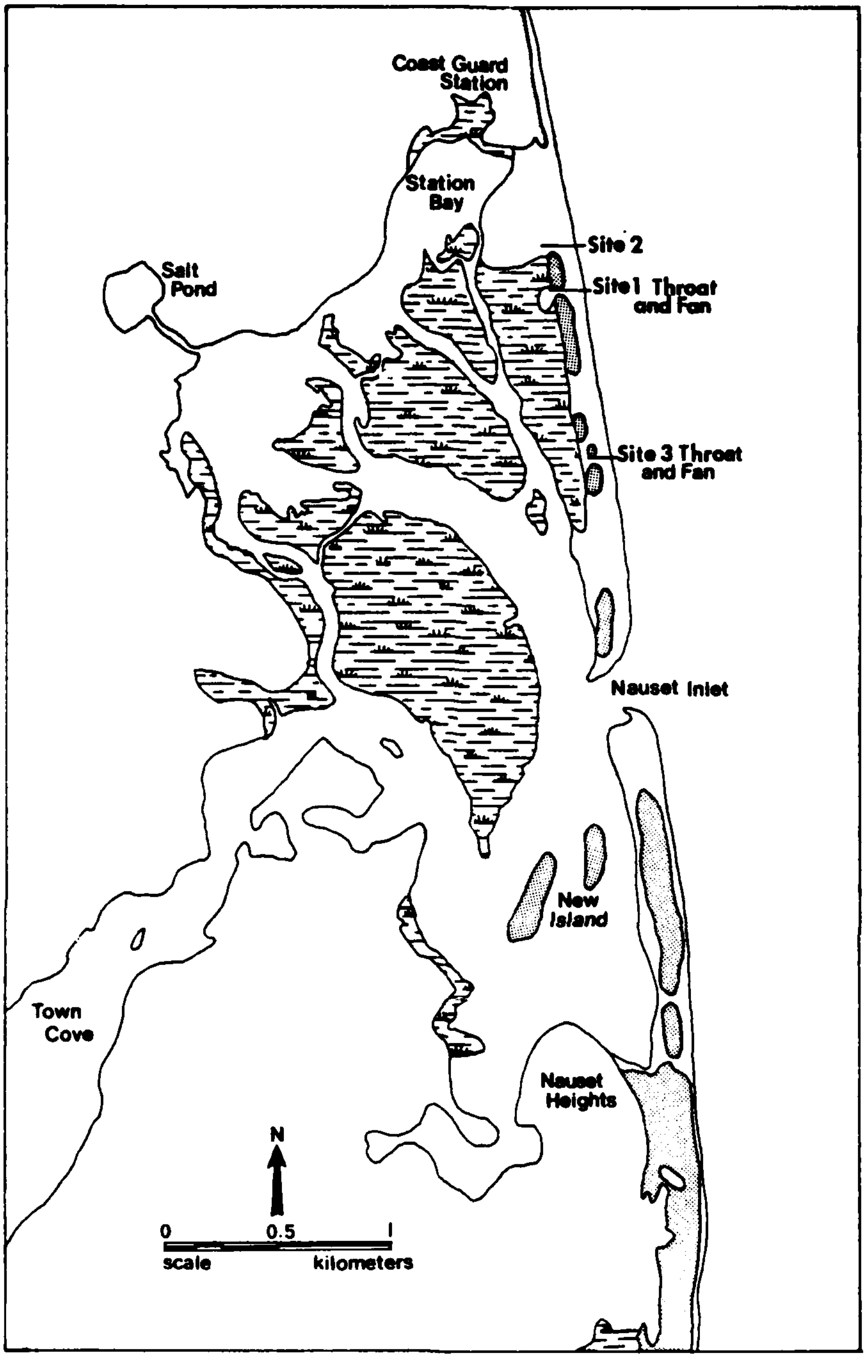


Figure 13. Site locations on Nauset Spit-Eastham, post-1978 storm.

b. Methodology. In order to quantify the amount of sand transported by overwash on Nauset Spit-Eastham, field survey data were collected. A grid of elevation stations was established at each study plot. The three research sites on Nauset Spit-Eastham were divided into five plots which were treated as separate physiographic units. Sites 1 and 3 were divided into "throat" and "fan" areas; site 2 consisted of only a washover fan since the throat meandered through the dune line.

Each plot was delimited by two base lines with transects established from one base line to the other. With the exception of site 1 throat, where transects were 3 meters apart, all transects were spaced at 5-meter intervals.

Temporary bench marks tied to a permanent U.S. Geological Survey bench mark were established at each site. Elevation readings were taken at flagged locations on each plot using an automatic level. Elevation stations were named according to transect number and distance from the eastern base line. The northern stake in the eastern base line was designated as 0 South (0S). Other transects were labeled according to their distance south and west of this northeastern stake.

Site 1 throat consists of a 24-meter base line with nine transects which extend 100 meters to the west. In 1977 this site consisted of the entire washover throat of site 1 with some adjacent dunes. Complete surveys of site 1 throat, from 0W to 100W along each transect, were conducted quarterly during 1977 and 1978, while surveys of the first 60 meters (0W to 60W), the area affected most by storms until February 1978, were conducted monthly and whenever major changes in elevation occurred. Two transects, 0S and 9S, were surveyed monthly from the ocean base line eastward toward the ocean to document changes in the beach profile.

Site 1 fan has a 60-meter base line with 13 transects extending 50 meters to the west. This site included the remnant of the 1972 washover, which was not overwashed again until 1978. The entire site was surveyed quarterly and after overwash deposition on the marsh.

Site 2 also has a 60-meter base line with 13 transects extending 50 meters to the west. When first overwashed in September 1976, site 2 consisted of a very small washover and surrounding unaffected marsh. This site was surveyed in 1977 and in February 1978, but has not been resurveyed since then because overwash has continued to alter the area, with almost each spring tide preventing revegetation.

Site 3 throat has a 30-meter base line with seven 50-meter transects extending west across the dune line; two transects (0S and 15S) extend to the ocean. In 1977 site 3 throat consisted of low profile dunes sparsely covered with vegetation. A small washover was formed by the storm on 10 May 1977, resulting in only minor erosion and deposition. This area was surveyed quarterly in 1977 and 1978 and has since been surveyed annually and after major storms.

Site 3 fan has a 30-meter base line with seven transects extending 60 meters to the west. When this site was first established in 1977, overwash had not occurred. Several of the elevation transects extended beyond the washover fan formed in 1978 to the first creek in the marsh. Surveys were conducted quarterly in 1977 and 1978 and have since been conducted annually.

In addition to the systematic measurement of elevation changes, sand plugs were used for monitoring the depth of erosion to calculate the gross sand deposition (King, 1951; Leatherman, 1976). A series of holes, 5 meters apart and 1 meter deep, were excavated along transect 9S at site 1 throat. A rod was held in each hole, which was then filled and tamped. Washover sand was spray-painted and dried. The rod was removed from the hole, and the resulting

column was filled with painted sand. Using the automatic level, the surface elevation was recorded at the top of the painted sand column. After an overwash, the top of each sand plug was relocated and the surface elevation determined by surveying. The amount of erosion, as well as the depth of poststorm sedimentation, can be determined from plug analysis (Fig. 14). Plugs were reset for later use by returning the painted sand column to the surface and resurveying the elevation of the top of the plug.

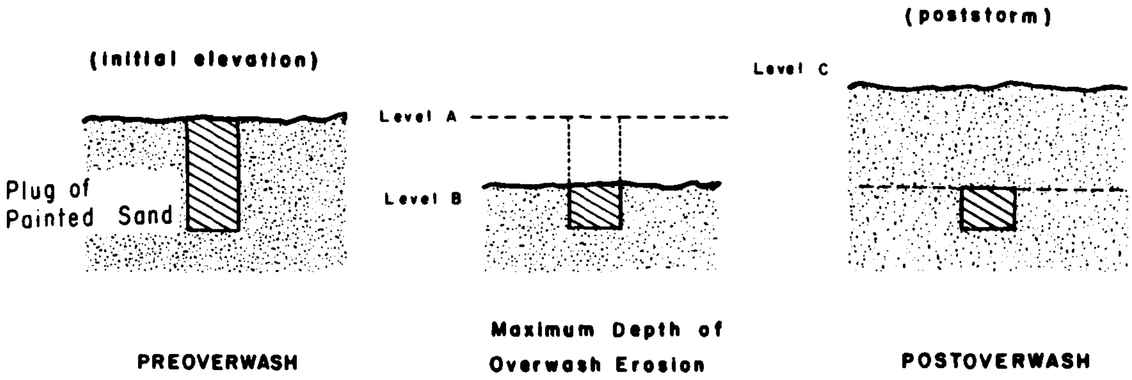


Figure 14. Sand plug method for determining maximum depth of erosion.

c. Analysis of Data. Large washovers were placed along Nauset Spit-Eastham during the 6 and 7 February 1978 storm (Fig. 13). Approximately three-quarters of the dunes were eroded during the storm; 1200 meters of washover breach resulted from storm erosion. One-quarter of the salt marsh adjacent to the dune line was buried by washovers. Sand was deposited up to 250 meters landward of the berm crest, burying the living salt marsh. The berm crest was displaced landward between 5 and 20 meters. The greatest shoreline erosion occurred about 100 meters south of the Coast Guard Beach parking lot where a long, shallow embayment developed during the storm (Fig. 10).

Overwash occurred at all three research sites on Nauset Spit-Eastham during the February 1978 storm. Bench marks and base lines were relocated after the storm so that exact measurements could be made.

(1) Site 1 Washover. Site 1 was the only washover on Nauset Spit-Eastham between 1972 and 1976. In June 1977 an elevation transect was established across the feature to document changes in elevation (Fig. 11). This transect extended the length of the throat (0W to 65W), crossed a pair of small dunes (65W to 90W), two sand roads (90W to 100W) and the 1972 washover fan (110W to 115W), and finally terminated in the unaffected salt marsh (115W to 140W). Beginning in November 1977, there were frequent small-scale overwashes during spring tides. Major overwashes occurred on 18 November 1977 and 6 and 7 February 1978. The 9 January 1978 northeaster, which caused large-scale overwash along other areas of Nauset Spit-Eastham, did not result in overwash at site 1. The entire site was surveyed before the storm in February in order to calculate accurately the amount of sand deposited by overwash without interference from aeolian processes. Sand plugs set in August 1977 were excavated after the February 1978 northeaster.

The entire transect was affected by overwash during the February 1978 storm (Fig. 11). The low backdunes were planed off, creating a relatively flat, gently sloping sand surface. The washover fan was expanded 25 meters westward into the marsh. The greatest deposition occurred over the sand road and on the adjacent 1972 washover fan. The berm crest was displaced approximately 15 to 20 meters landward. Sand plug data showed that along the transect through the throat area, vegetation was displaced by the overwash surges (Fig. 11). The more cohesive substrate of the marsh resisted any erosion; the marsh was subjected to deep burial (from 0 to 85 centimeters).

While approximately 1200 meters of the 2100-meter-long dune line on Nauset Spit-Eastham was eroded during the February storm, dunes at site 1 were eroded only 4 to 10 meters on either side of the throat (Fig. 15). The throat section through the dune line was straightened, and the washover fan was enlarged in all dimensions (Fig. 16). Approximately 5000 square meters of sand was added to the fan, but the feature retained the same general shape present in 1972. About 8000 cubic meters of sediment was added to site 1 washover in February 1978.

(a) Site 1 Throat. Extensive erosion and redeposition took place at site 1 throat during the February 1978 storm. Three-dimensional plots from elevation data were developed for 5 and 19 February 1978 (Fig. 17). The vegetated dune north of the site eroded landward, and the large, wind-shadow dune south of the throat eroded to a position outside the plot. Low areas were filled and high areas were flattened. For the 149 elevation stations surveyed in 1977 and resurveyed in 1978, mean net depth of burial was +0.11 meter (σ = 0.41 meter) with an erosional range of 0.78 meter and a depositional range of 1.02 meters. The standard deviations of the elevation points surveyed in 1977 (0.60 meter) and 1978 (0.32 meter) reflect the flattening effect of overwash on a dune community. The shallowest deposition, less than 25 centimeters, occurred in the seaward part of the throat where low elevation was maintained with little net change. The greatest deposition occurred on the marshward edge of the 1977 washover throat.

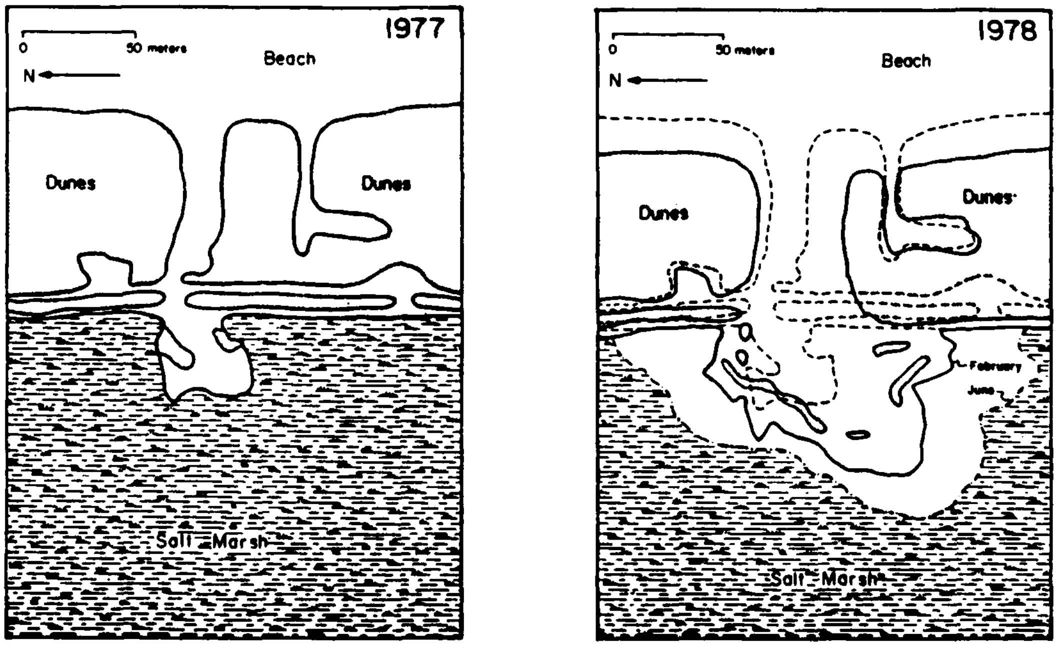


Figure 15. Site 1 before and after February 1978 storm.

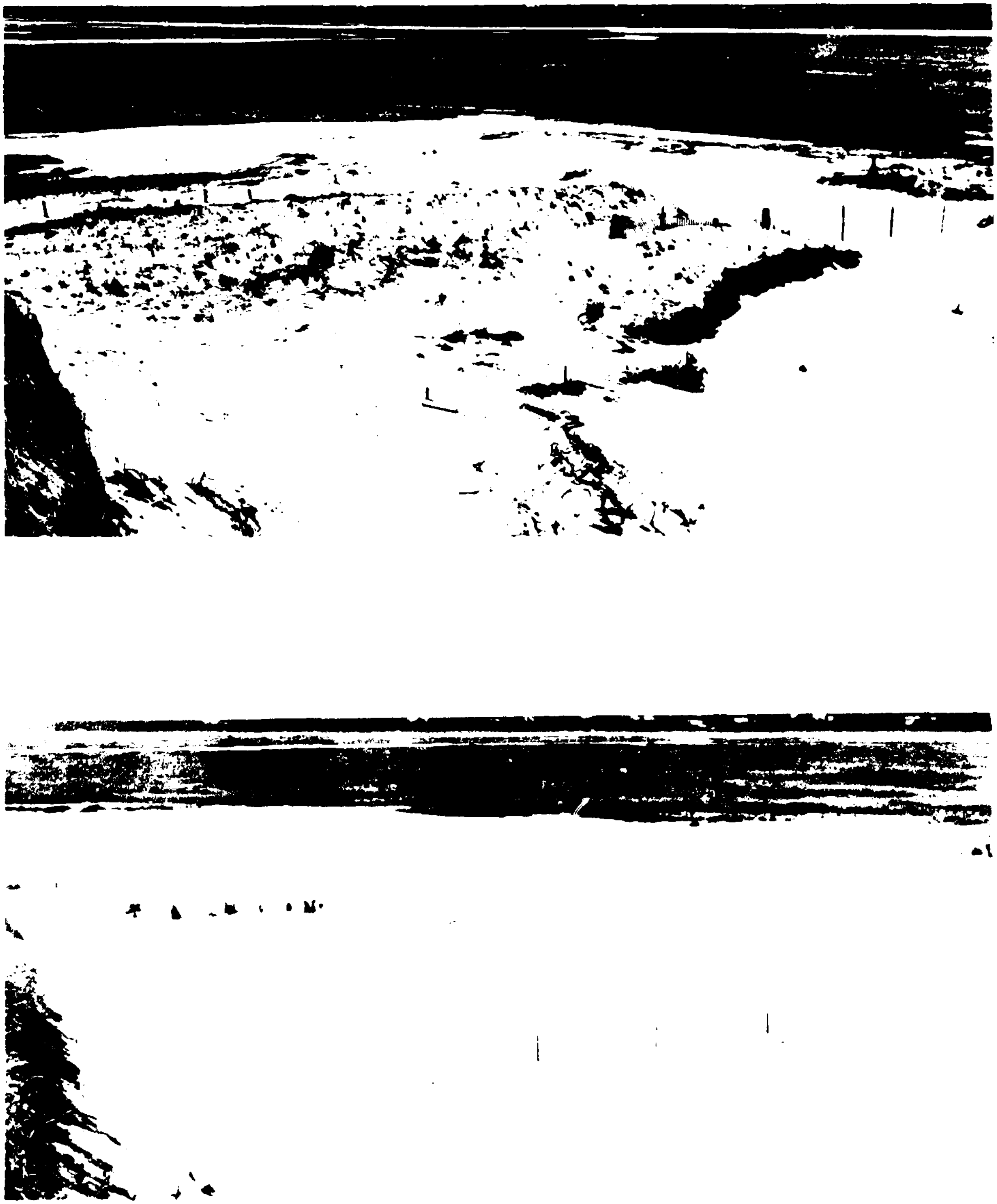


Figure 16. Prestorm and poststorm photos of site 1, February 1978.

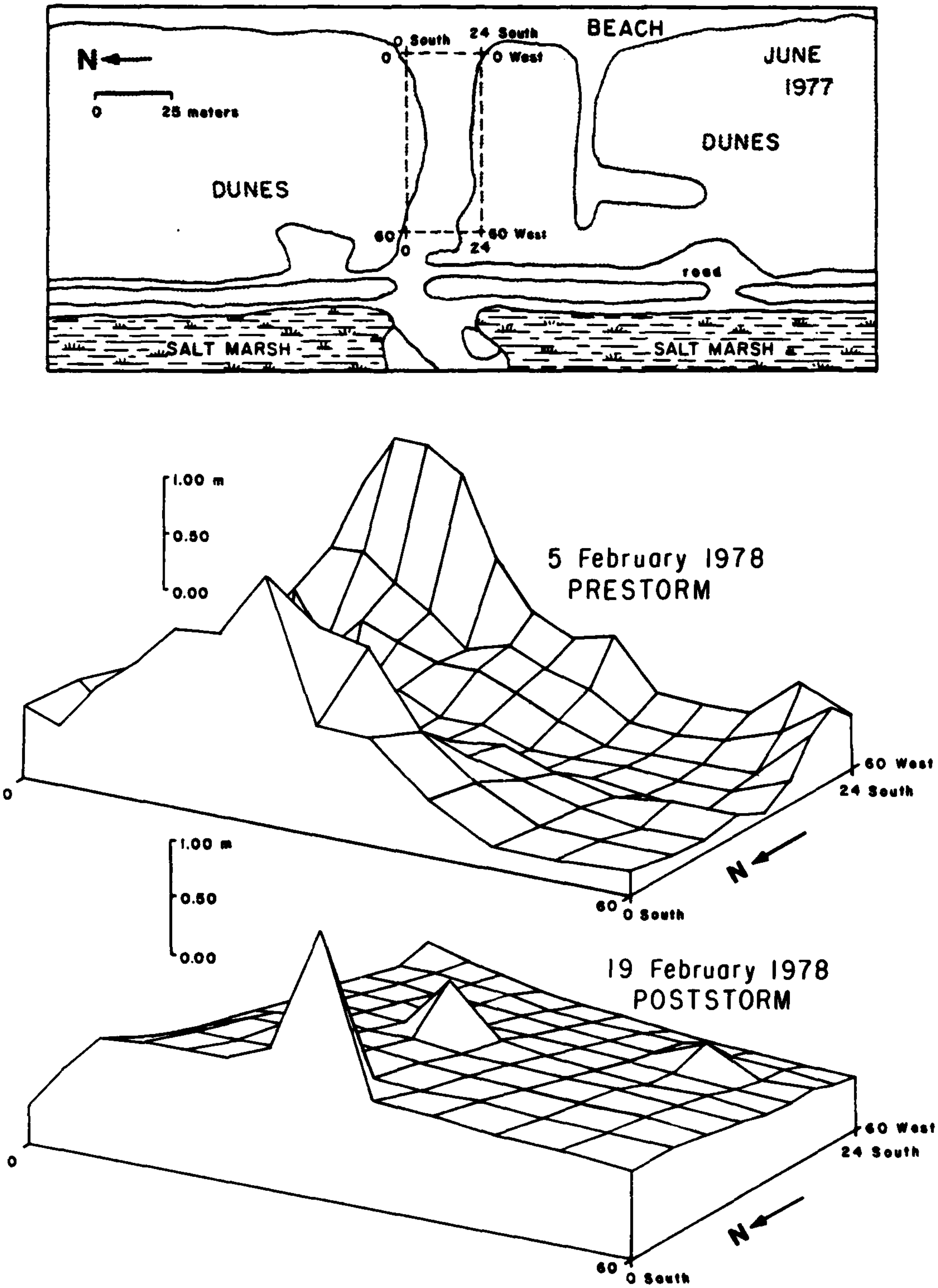


Figure 17. Prestorm and poststorm three-dimensional plots of site 1 throat, 1978.

(b) Site 1 Fan. Site 1 fan has been the primary research site for study of the revegetation process on washovers. The February 1978 storm deposited large quantities of sand in this area, burying the developing dune line on the previous fan (Fig. 11). During the February northeaster, the fan center was displaced southward due to storm wave approach and previous back barrier topography (Fig. 15), and 30- to 40-knot winds from the northeast drove overwash surges to the southwest. A washover created in 1938, north of site 1, was only marginally evident in 1978; however, the slight increase in elevation resulting from the washover caused swashes to be deflected to the south.

A three-dimensional plot was developed from elevation data collected before and after the storm at the 5- by 5-meter grid at site 1 fan (Fig. 18). The greatest sand deposition (85 centimeters) occurred near the center of the fan, located at the southeast corner of site 1 fan plot (Figs. 15 and 18; 60S to 0W). The northwest corner of the site was not affected by the washover deposit (Fig. 15; 0S to 50W). Mean sand deposition for site 1 fan was 0.62 meter (σ = 0.35 meter). The elevation range increased from 1.01 meters in 1977 to 1.79 meters in 1978, reflecting large deposits of sand in the center of the fan and no sand deposition at the edge of the plot. Although some dune vegetation had been present on the washover fan in 1977, site 1 fan was predominantly a salt marsh with very little topographic relief. The effect of overwash in this area increased topographic irregularities (1977, σ = 0.24 meter; 1978, σ = 0.49 meter), partly because the area had been a salt marsh and partly because site 1 fan was located at the edge of the washover.

(2) Site 2 Washover. Site 2 overwashed during both the January and February 1978 northeasters. The meandering throat present during the creation of the washover in fall 1976 was straightened by the January 1978 storm. The February northeaster completely eliminated the dunes seaward of site 2, engulfing the area in a massive washover. Pits dug in the substrate showed that approximately 0.20 to 0.50 meter of sand had been deposited over the salt marsh. Surficial drift material was not present after the storm. A lag layer of shells deposited during the storm was present throughout the area.

Site 2 continued to overwash throughout February and March 1978 and during the spring tides of April, May, and June, periodically exposing and covering the vegetation present during 1977. Plants did not recover from overwash burial, and colonization from drift material did not take place during the growing season at site 2. The fan has, therefore, remained active in terms of sediment transport (overwash and aeolian) and has been continually subject to saltwater flooding. Neither elevation surveys nor vegetation samplings were continued at this site after the February 1978 northeaster.

(3) Site 3 Washover. Site 3 has perhaps proved to be the most interesting area on Nauset Spit-Eastham. This site was established in June 1977 because the dune profile was very low and it appeared to be a location for possible future overwash activity. In 1977 a small breach at site 3 and an adjacent small breach in the foredune were the only breaks in the otherwise continuous dune line in the area. Storms on 10 May and 10 June 1977 eroded a small channel into the dunes, flooding and killing any dune vegetation. Overwash did not penetrate the back of the dune line and very little sand was eroded or deposited. The February 1978 northeaster penetrated the dune line in the same position, eroding a slightly larger channel. The dunes in the area remained intact as overwash surges passed over these low dunes without causing significant erosion.

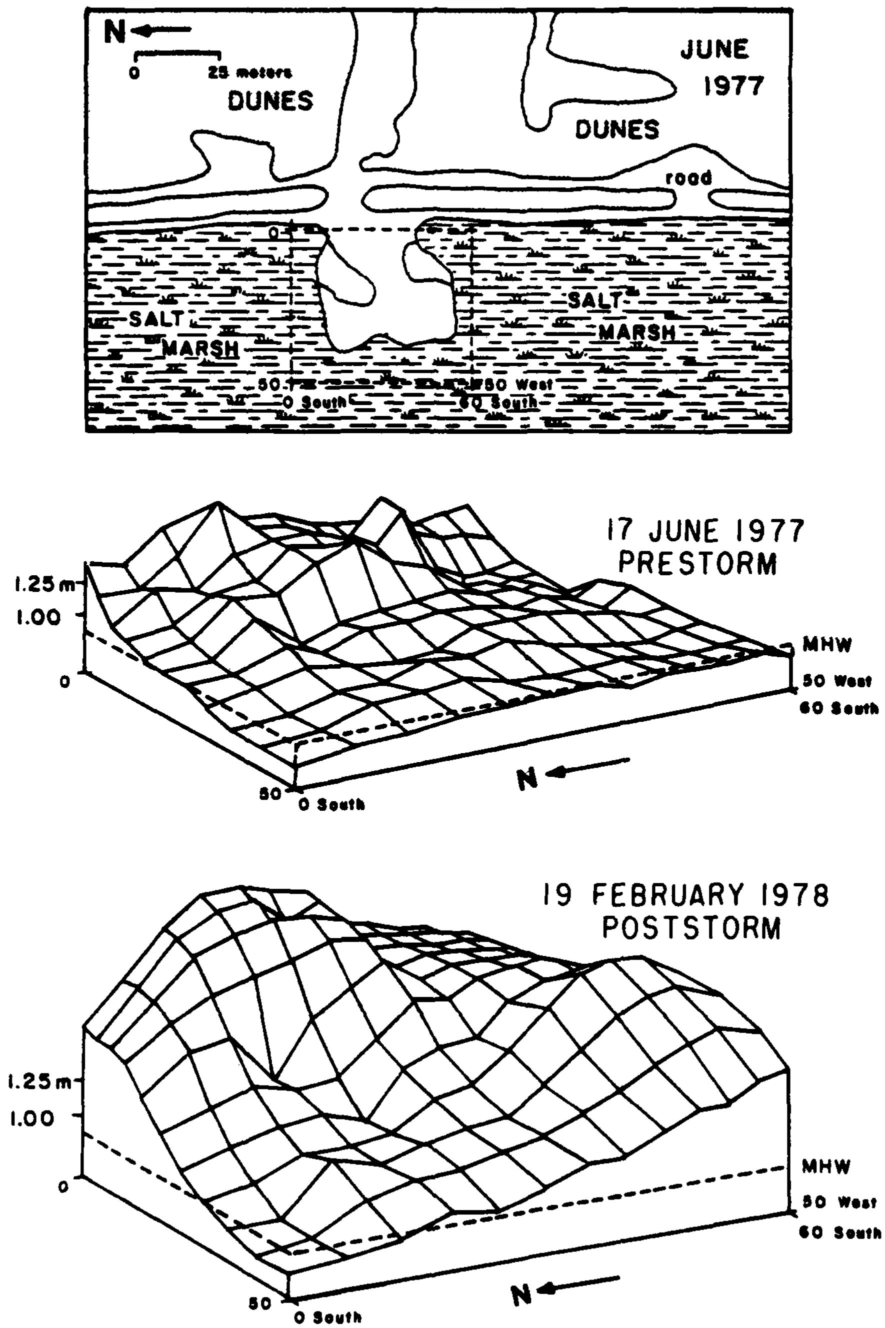


Figure 18. Prestorm and poststorm three-dimensional plots of site 1 fan, 1978.

Overwash also occurred to the north and south of site 3. Only 5 meters of dune to the north and 15 meters of dune to the south remained after the storm, leaving site 3, once the only washover in the area, stranded among the washover flats. Washover sediments from the north and south channels coalesced on the marsh at site 3.

The centerline transect through site 3 throat and fan (15S) extended west and was surveyed before and immediately after the February storm (Fig. 19). Sand deposition occurred as far as 135 meters west of the 1977 berm crest. The greatest recorded deposition on Nauset Spit-Eastham resulting from the February storm was recorded at site 3, where 1.65 meters of sediment was deposited on the old road bed at 160W. The beach profile was planed off and the storm berm was displaced 15 meters landward of its prestorm position. The total amount of overwash deposition was 400 cubic meters per running meter of dune overtopping or breach.

(a) Site 3 Throat. Site 3 throat experienced less extensive erosion and deposition during the February storm than did site 1 throat, being a major overwash channel. Three-dimensional plots of site 3 were made from elevation data collected at the 5- by 5-meter grid in August 1977 and June 1978 (Fig. 20). The backdune area (40W to 50W) was steeply scarped (1 meter) in 1977 at the edge of the road, and overwash surges eroded the outer 1 meter of the area. In vegetated areas, such as at site 3 throat, the greatest deposition occurred toward the back of the dune line; little deposition occurred near the new berm crest. From the 77 elevation points surveyed for the 5- by 5-meter grid, mean elevations relative to a USGS bench mark were calculated for 1977 (1.78 meters) and 1978 (1.94 meters). A comparison of elevation statistics for 1977 (σ = 0.44 meter; range = 2.10 meters) and 1978 (σ = 0.15 meter; range = 0.69 meter) shows the flattening effect of overwash on dunes.

(b) Site 3 Fan. Site 3 fan was not eroded during the February storm, but was entirely buried by washover sand. Three-dimensional plots of elevation data taken in August 1977 and June 1978 show that the road and the salt marsh were subject to deep burial (Fig. 21). The greatest deposition occurred closest to the sand road. From the 56 elevation stations surveyed for the 5- by 5-meter grid, the mean elevation and range were calculated for 1977 (0.15 meter; range = 0.28 meter) and 1978 (0.77 meter; range = 0.67 meter). The standard deviations (1977, σ = 0.08 meter; 1978, σ = 0.19 meter) show the increase in slope in the marsh caused by overwash burial.

4. Aeolian Reworking.

a. Introduction. Although a considerable amount of sand was deposited by overwash on Nauset Spit-Eastham, much of this sediment has been redistributed during interstorm periods. Tidal currents have reworked sand along fan margins, but wind has been the principal means of redistributing the sediment. Prevailing northwest and southwest offshore winds during the winter often exceed 30 knots per hour and frequently average 10 to 15 knots per hour. Since this wind field is generated by Canadian high-pressure cells, strong winds are accompanied by clear weather, resulting in maximum transport because the sand is dry.

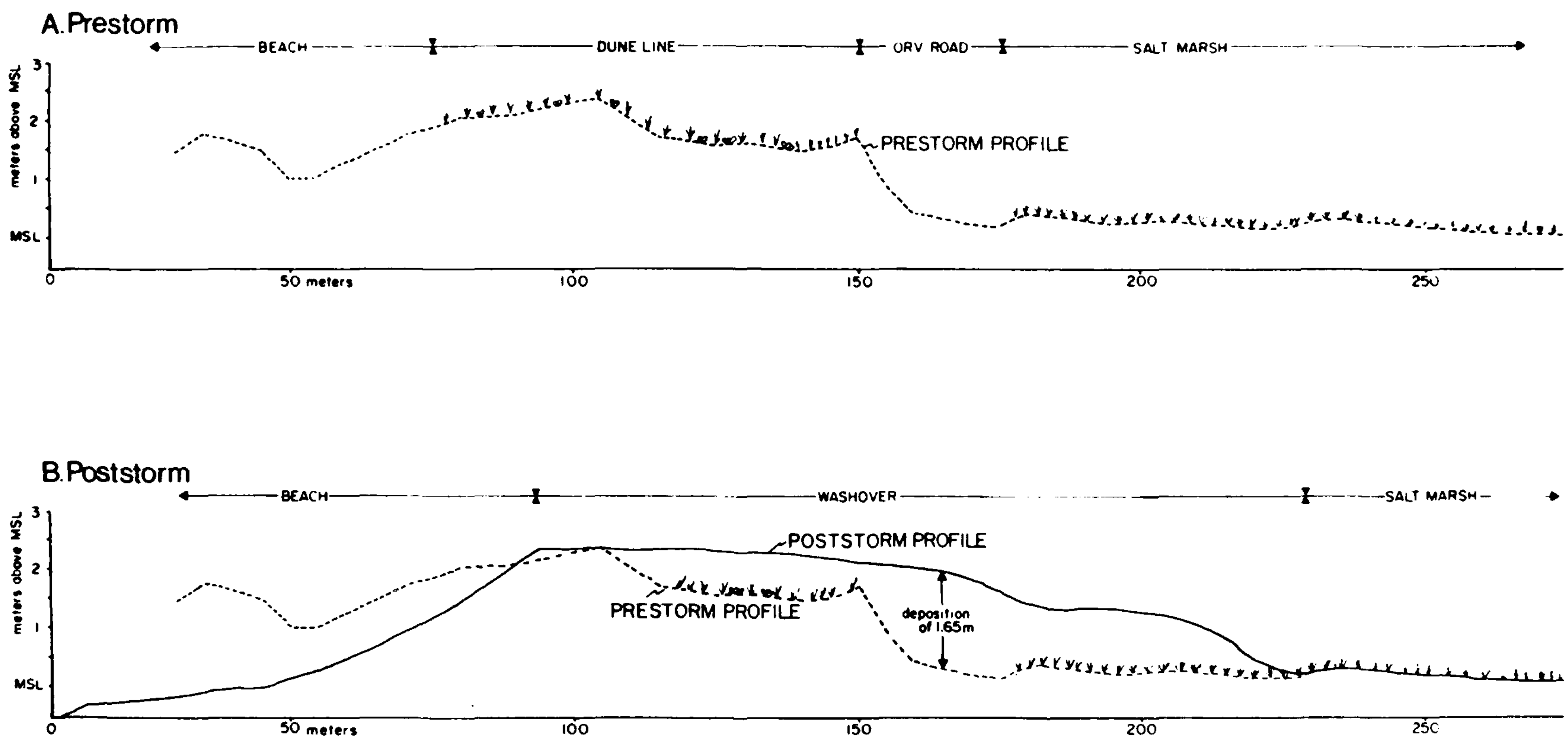


Figure 19. Elevation transect across site 3 showing topographic changes resulting from the February 1978 storm.

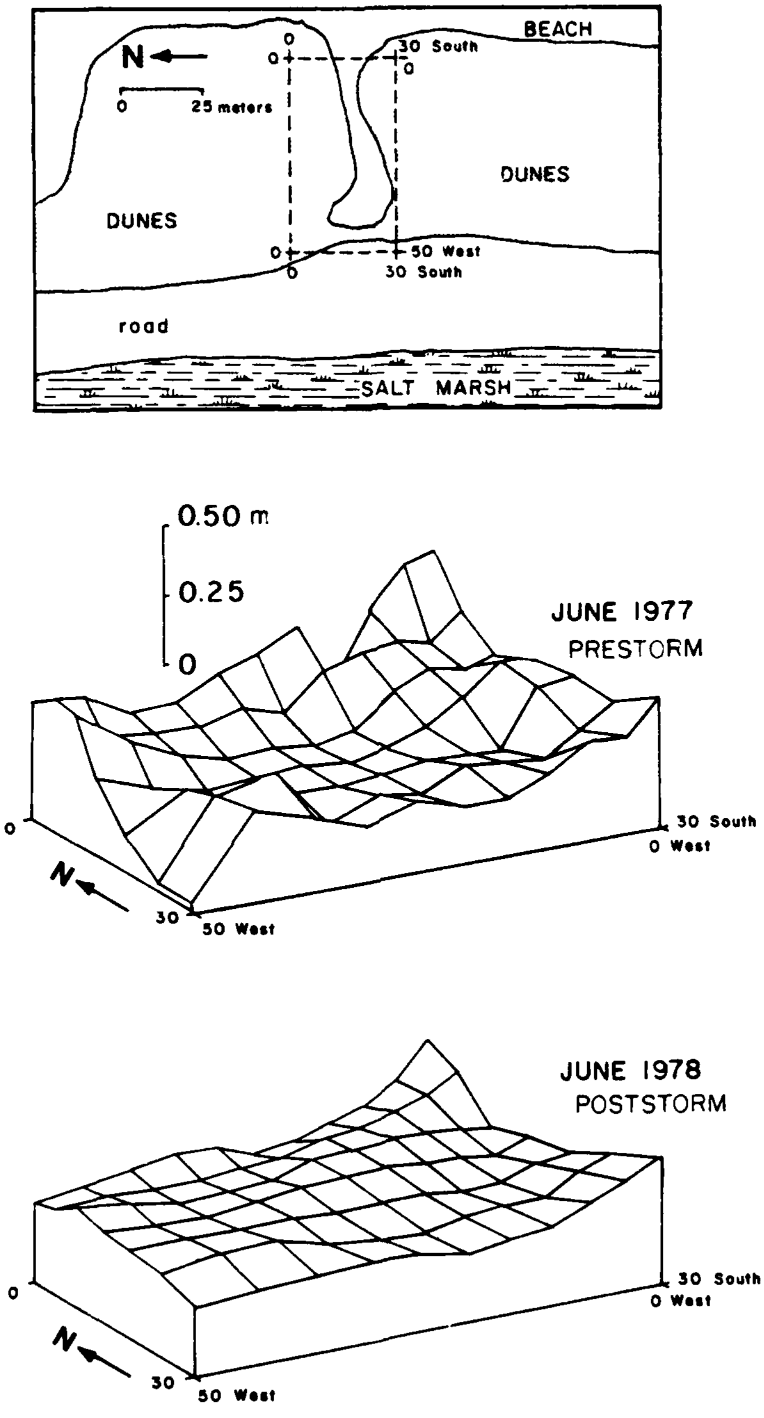


Figure 20. Prestorm and poststorm three-dimensional plots of site 3 throat, 1978.

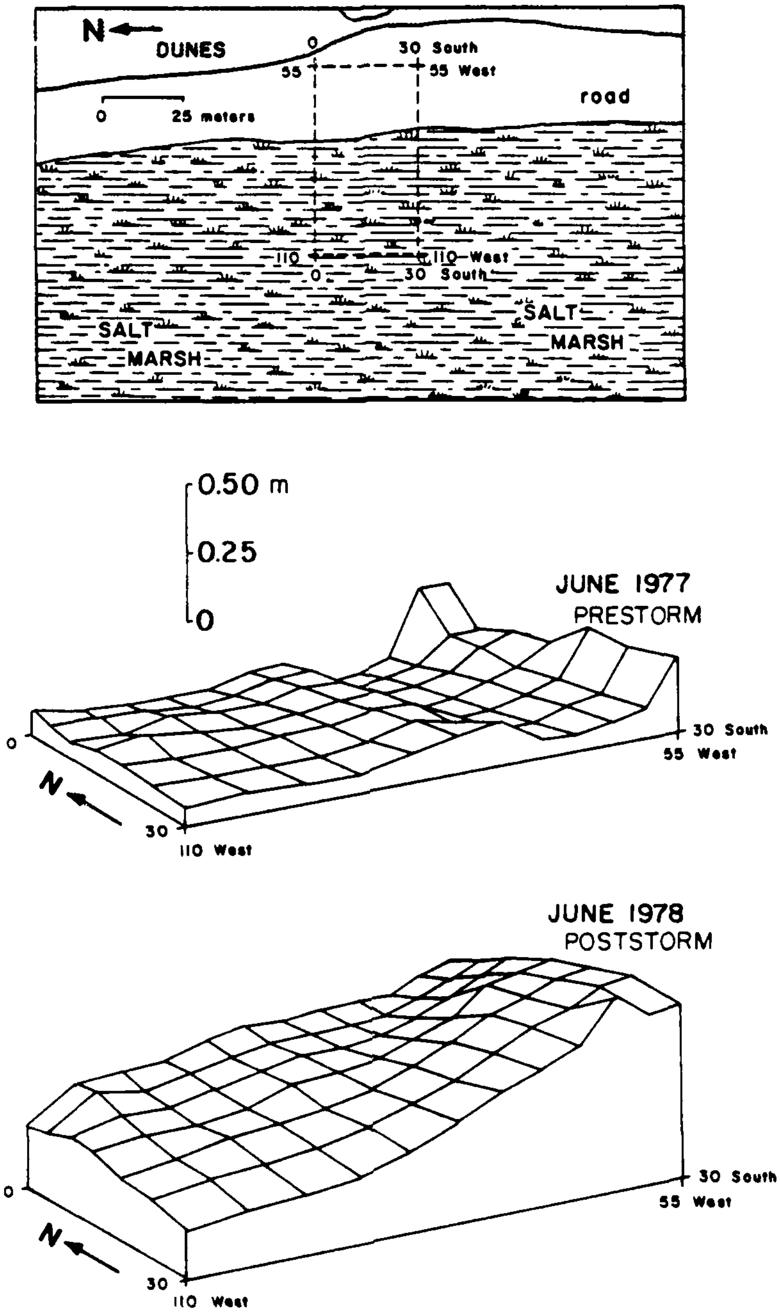


Figure 21. Prestorm and poststorm three-dimensional plots of site 3 fan, 1978.

b. Analysis of Data.

(1) Deflation of Dune-Throat Areas. Deflation of washover throats was studied at sites 1 and 3 on Nauset Spit-Eastham. Site 1 throat was surveyed for 18 months after the February 1978 storm to document deflation of washover sediment from an area where all vegetation had been removed. The throat of site 3 washover was studied to document deflation where there was deposition on top of living dune vegetation.

(a) Site 1 Throat. During the February 1978 northeaster, 288 cubic meters of sand was deposited at site 1 throat (Fig. 17). The throat was very flat (σ = 0.32 meter), decreasing gradually in elevation west of the berm crest. Only a small remnant of the north vegetated dune and two piles of drift material interrupted the planar feature. Three-dimensional plots of site 1 throat were constructed from survey data collected in April, June, and October 1978 and in June 1979 to illustrate the deflation and overall changes in the throat (Fig. 22).

Within 2 months, site 1 throat had lost 194 cubic meters (67 percent) of the washover sediment deposited during the February 1978 storm. The southwest corner of the plot (18S to 24S, 30N to 60W) was deflated by as much as 72 centimeters. The prograding edge of a large wind-shadow dune, which developed against the scarped dune south of site 1 throat, appears in the southeast (15S to 24S, 0W to 25W) corner of the plot. The elevation in this area increased as much as 63 centimenters.

Between April and October 1978, very little change occurred at site 1 throat because wind velocities were low. The back and center of the throat continued to deflate and the wind-shadow dune enlarged. Only 35 cubic meters of sand was lost between April and June; 78 cubic meters was lost between June and October 1978.

Between October 1978 and June 1979, site 1 throat lost another 257 cubic meters of sand for a total of 564 cubic meters, approximately twice the initial overwash. The berm crest in June 1979 was slightly lower (10 centimeters) than the berm crest on 5 February 1978 when overwash occurred. A lag layer of heavy cobbles had developed by June 1979, slowing aeolian deflation of the throat.

Two years after the 1978 northeaster, site 1 throat had not been stabilized by vegetation. Drift line vegetation developed each spring in debris, but these plants were eroded by either aeolian deflation or overwash the following winter. Site 1 throat remained an active washover channel, preventing the closure of the breach in the dune line.

(b) Site 3 Throat. Site 3 provided a very different set of conditions for study. Overwash overtopped the dunes at site 3, eroding the dunes south of the washover channel and 30 meters into the dune line in the center of the plot. Approximately 50 percent of the dunes at site 3 throat were eroded. Three-dimensional plots of site 3 throat were constructed from field surveys conducted in June and August 1978 and August 1979 (Fig. 23).

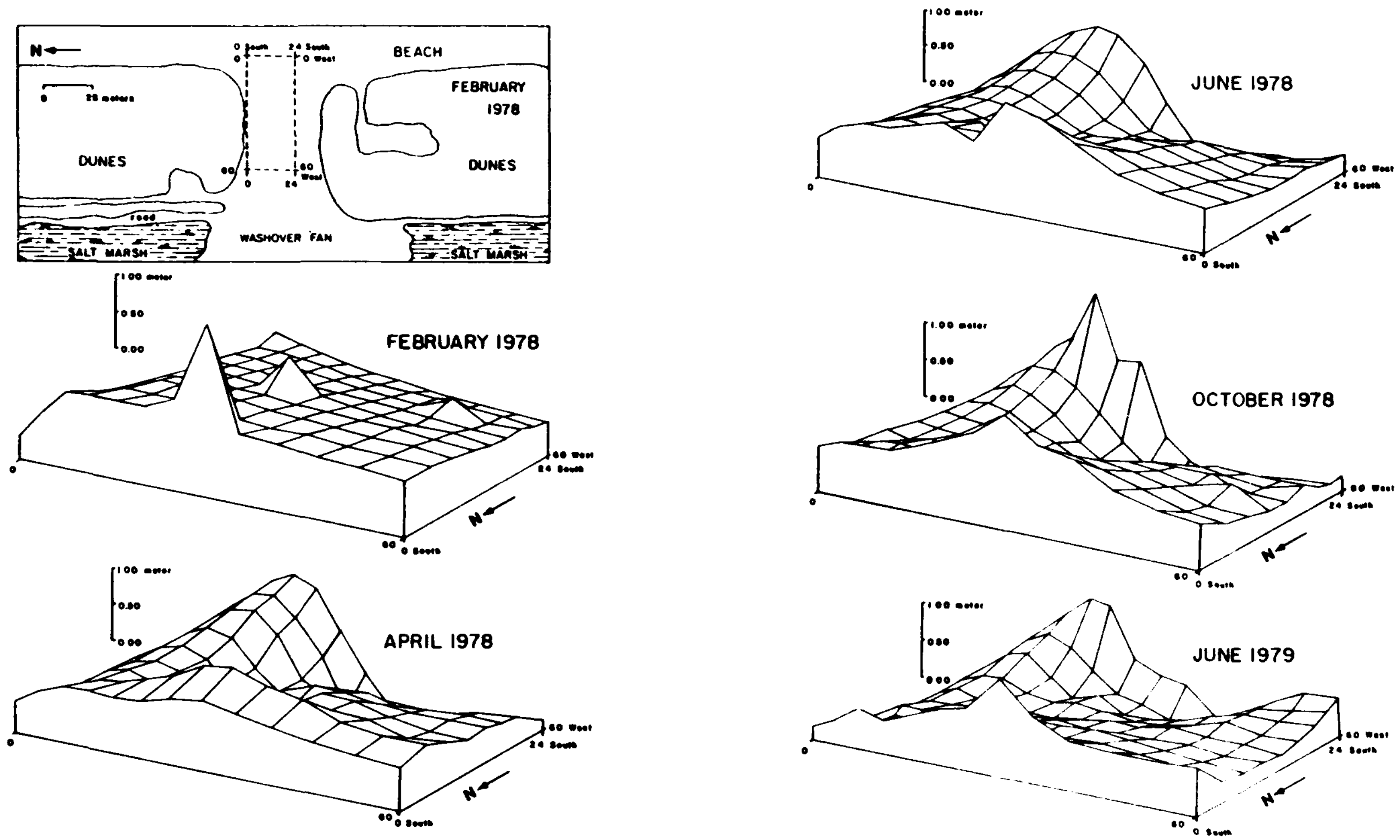


Figure 22. Series of three-dimensional plots showing deflation of site 1 throat.

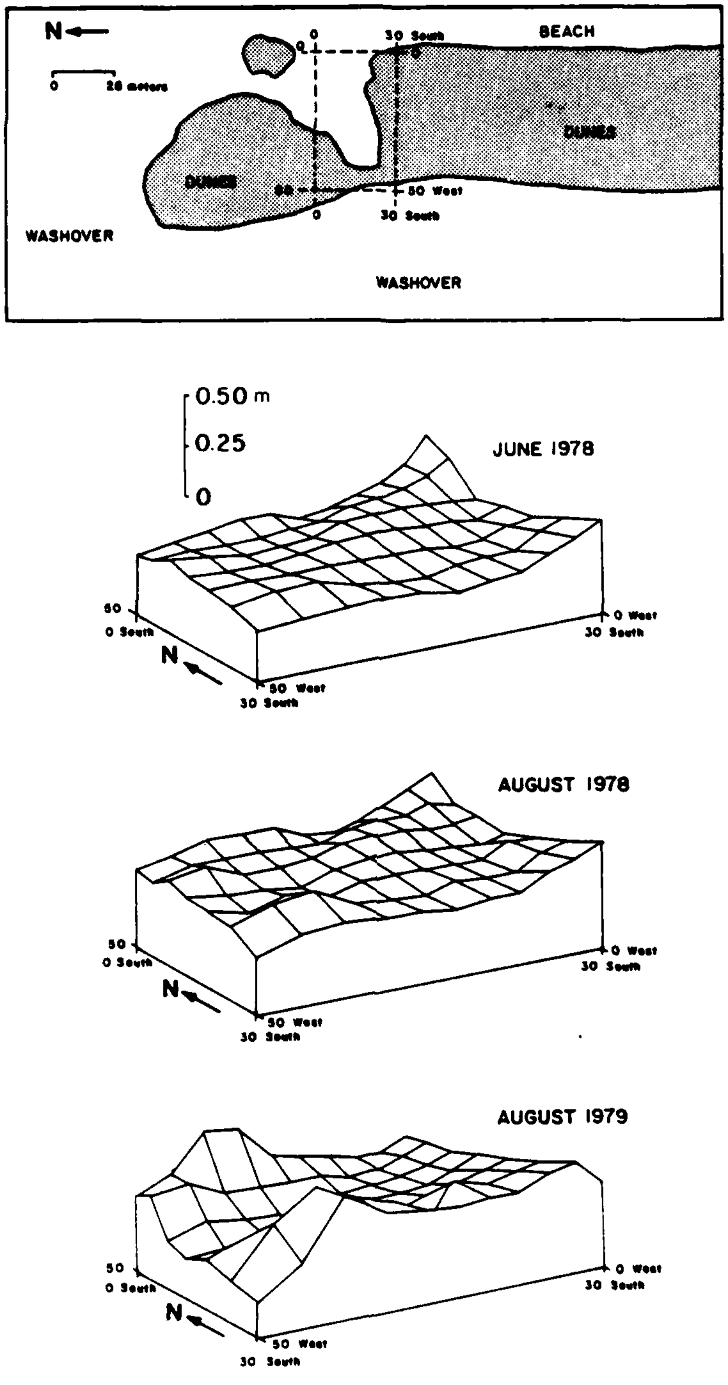


Figure 23. Poststorm three-dimensional plots of site 3 throat, 1978.

A complete grid survey of site 3 was not conducted after the February 1978 storm until June. Between June and August 1978, 312 cubic meters of sand were added to site 3 throat (Fig. 23). Areas with recovering dune vegetation in the northwest and southwest corners of the plot had increased in elevation by 15 centimeters. This situation contrasts with the large-scale deflation at the nonvegetated throat area at site 1.

During the winter of 1979, site 3 again overwashed. A channel was cut through the back of the dune line. Remnant dunes in the front 30 meters of the plot were leveled. By August 1979 the dunes in the northwest and southwest corners of the plot were substantial features (Fig. 23). *Ammophila breviligulata* had trapped as much as 30 centimeters of sand. The decrease in elevation of surrounding unvegetated regions caused by overwash scouring and aeolian deflation further increased the topographic relief. Drift lines deposited at the base of these dunes during overwash increased the areal vegetated surfaces. Unlike site 1, this site had in 2 years begun to stabilize with the development of remnant dunes landward of the prestorm dune line.

(2) Deflation of Fan-Flats Areas. Site 1 fan was surveyed after the storm to document the deflation of sediment from a washover fan. During the February storm, 1920 cubic meters of sand was added to the research plot at site 1 fan. Approximately 8000 cubic meters of sediment was deposited in the entire washover feature. Since the plot was situated at the outer edge of the washover, the surface sloped steeply toward the northwest corner (0S, 50W), which was unaffected by the storm (Fig. 24).

Spring tides and high winds reworked the deposit, enlarging the fan in all directions (Fig. 15). Between February and March 1978, only 60 cubic meters was deflated from the plot (Fig. 24). The highest points in the plot at the northeast corner (15S to 25S, 0W to 15W) were reduced in elevation by about 15 centimeters. Areas on the south side of the plot increased by as much as 22 centimeters. Some sediment was drawn bayward by spring tides. Six elevation stations in the northwest corner of the plot that had not been affected by overwash were buried by up to 7 centimeters of sand only 1 month after the storm.

The loss of sediment from the fan continued between March and August 1978. The greatest deflation occurred in the spring months. Highest elevations were deflated as much as 25 centimeters; the northwest corner increased in elevation by an additional 5 to 20 centimeters. Areas with drift lines at the outer edges of the fan did not deflate as rapidly as barren areas. The fan was enlarged by as much as 90 meters by wind and tides expanding the edges of the feature (Fig. 15). Overall, 300 cubic meters of sand was lost from site 1 fan between March and August 1978.

The plot was resurveyed in March 1979 (Fig. 24). Although site 1 fan had overwashed during the winter of 1978-79, less than 10 centimeters of sand was added to any area of the fan. During the winter, high winds deflated all the areas not stabilized by vegetation. Only in drift-line areas at the outer edge and in the northwest corner did the plot remain stable. As much as 44 centimeters of sand was lost at some elevation stations. The northwest corner of the plot increased in elevation by 20 centimeters so that the entire site, which had been a salt marsh, was now above MHW. The plot was becoming

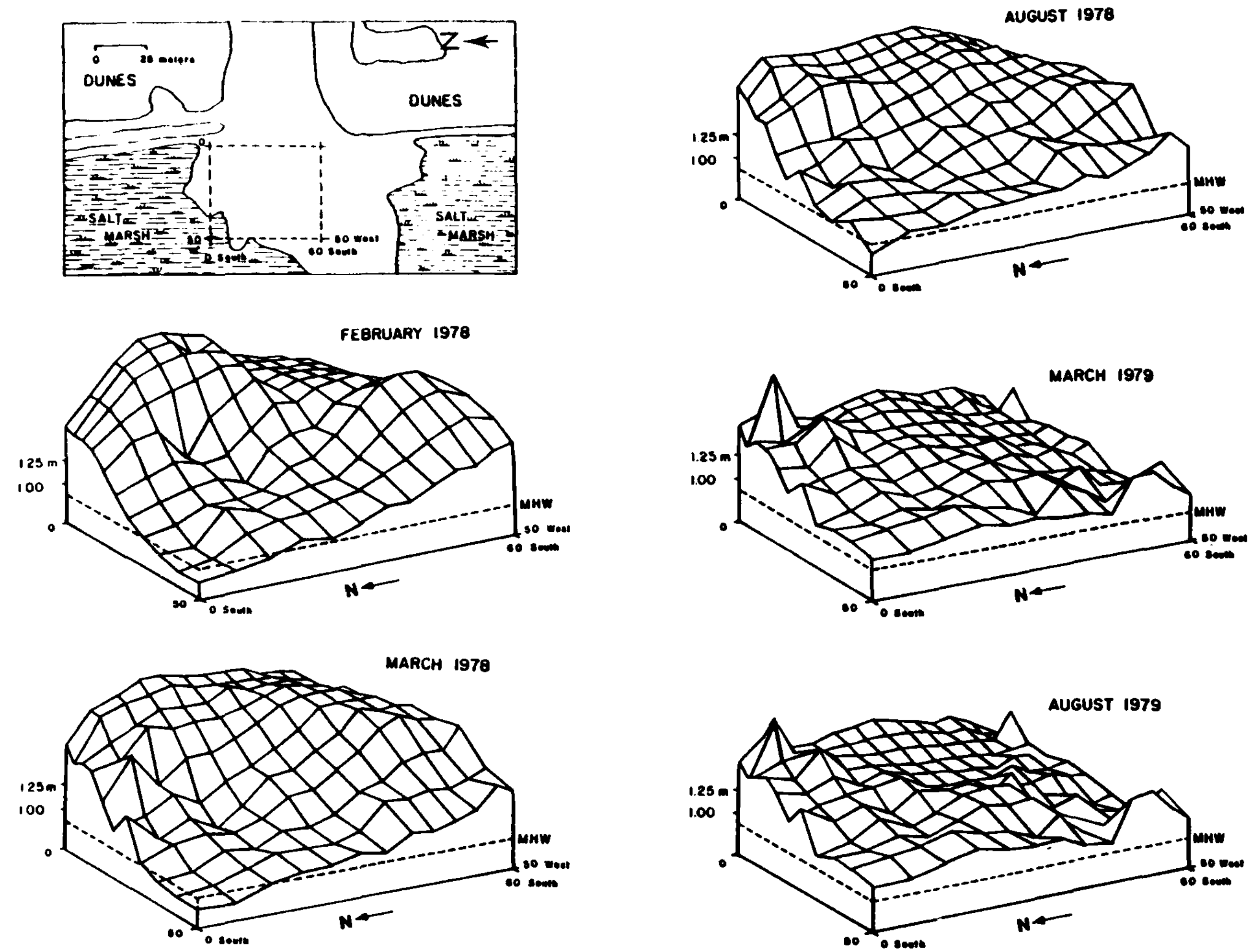


Figure 24. Series of three-dimensional plots showing deflation of site 1 fan.

increasingly flatter as reflected by the standard deviation of the 120 elevation points. In August 1978 the standard deviation was 40 centimeters; in March 1979 the standard deviation was 24 centimeters. Low dunes, evident in the location of drift lines, developed as a result of differential deflation of surrounding areas and not by sediment accumulation in the vicinity of plants. A total of 660 cubic meters of sand was lost from site 1 fan between August 1978 and March 1979 (Fig. 24).

By August 1979 an additional 140 cubic meters had deflated from site 1 fan, principally in unvegetated locations. Drift lines were formed during the late spring abutting low drift-line dunes established in 1978. These drift lines were well vegetated in August 1979 and accounted for a larger stabilized area.

During the 18 months in which deflation at site 1 was studied, 1160 cubic meters or 60 percent of the initial washover deposit was lost from the plot. The greatest deflation was 75 centimeters, which was lost from the south side of the area. The greatest accretion occurred at the northwest corner, which was unaffected by storm sedimentation, where 32 centimeters of aeolian and tide-borne sediment had accumulated.

A small amount of sediment lost from washover fans was blown into the surrounding salt marsh, forming low mounds around dense stands of *Spartina patens* (saltmeadow cordgrass) and *Spartina alterniflora* (salt-marsh cordgrass). The vast majority of sediment deflated from washovers on Nauset Spit-Eastham, however, was blown seaward by northwest and southwest winds. Lost from the back barrier, about half of this sand was transported to the beach and about half was trapped in remnant dunes.

To determine the relative amount of sand that was added to the dune line at the periphery of the site 1 washover fan, elevation transects were established at 5-meter intervals in the dunes to the north and south of site 1 throat. At each elevation station, a hole was excavated around *Ammophila breviligulata* tillers. Each spring the vertical rhizomes of *Ammophila breviligulata* extend through the sand deposited during the winter. The apical meristem, which remains approximately 6 to 8 centimeters below the sand surface, near the interface between wet and dry sand, produces many leaves along a very short section of rhizome. This vertical section of rhizome with many nodes and internodes can be used to locate the relative position of a sand surface that remained stable for several months (Olson, 1958; Disraeli, 1982).

Using the morphology of *Ammophila breviligulata*, dune-building rates were determined in the area peripheral to site 1 throat. Seven transects from this area are shown in Figure 25. The greatest deposition occurred along these transects in positions nearest the washover. Sediment was transported as far as 150 meters from the back-dune edge and to an elevation more than 5 meters. Maximum deposition was 71 centimeters, 10 meters south of site 1 throat. Approximately 1000 cubic meters of sand was deposited in the dunes to the southeast of site 1 by the dominant northwest winds; 450 cubic meters accumulated north of site 1. During this same period, approximately 2800 cubic meters of sand was deflated from the entire washover fan. Therefore, approximately 52 percent of the sediment deflated from the fan accumulated in peripheral dunes.

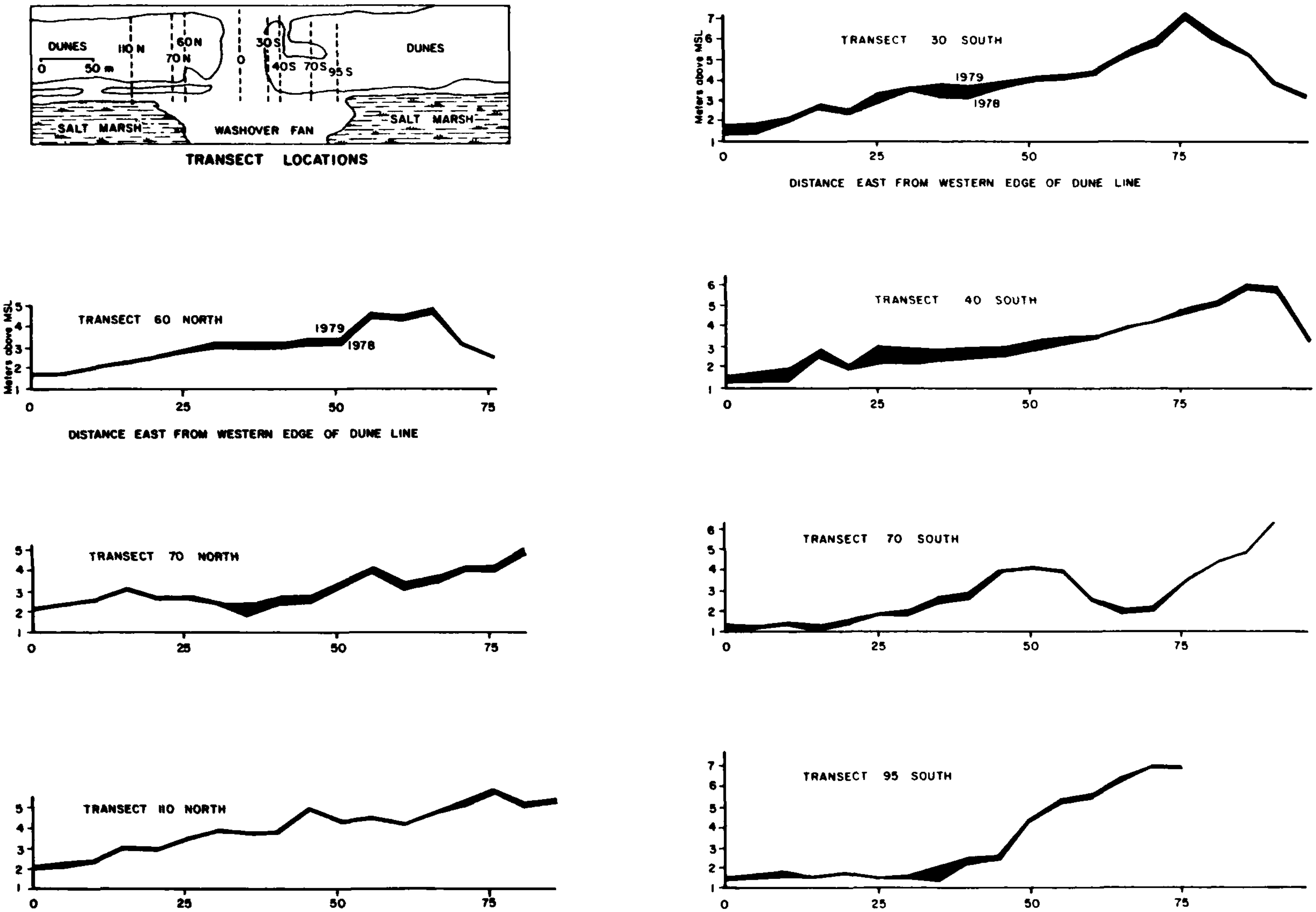


Figure 25. Sediment accumulation in the dunes peripheral to site 1 washover.

(3) Stabilization of Washovers.

(a) Washover Throats. Stabilization of washover throats is dependent on the size of the throat, the frequency of overwash in the area, and the orientation of the barrier. Small washover throats may quickly close if overwash pressure is removed. Many washovers, like site 2 in 1976, begin as meandering channels through the dune line. Dune vegetation can grow rapidly into the channel trapping sand and repairing the breach. On Nauset Spit, winds from the northwest and southwest often build wind-shadow dunes, which help to close these breaches. Winds from the northeast and southeast may be deflected by the dune line, so that sand is blown along the shoreline and deposited in embayments and breaches, maintaining a smooth seaward contour to the dune line.

Large features remain open for longer periods of time. If a throat is broad and oriented parallel to prevailing winds, a channel may be eroded by the wind to an elevation below the threshold level for washover. An area may remain susceptible to washover for many years, enlarging until peripheral dunes are completely leveled.

A washover throat may deflate to the proximity of the water table, resulting in wetter surface sands which are not easily moved by the wind. Large-size material, such as cobbles and gravel, along with sand, are deposited in the throat by washover surges; smaller material is carried farther onto the washover fan. With the deflation of each successive washover, the lag surface becomes more concentrated. At site 1 throat in 1977, a pavement of cobbles and heavy minerals indicated considerable deflation. Once the surface has stabilized, plant colonization can begin.

(b) Washover Fans. Small washovers are common along Nauset Spit and are often rapidly stabilized unless continually affected by subsequent overwashes or human impact, such as pedestrian trampling or off-road vehicle trespassing. In some cases, a small fan will be enlarged by future overwashes; this is particularly common when the barrier dune line has a low elevation profile and is very narrow.

Following overwash, the prevailing offshore winds deflate these fans. Much of the washover sand is blown onto the beach face or deposited on the back dunes adjacent to the fan. Lag layers of larger size material may form, but their occurrence is somewhat minimized since material of this size range is not frequently transported beyond the washover throat.

If the depth of sediment burial is shallow (less than 30 centimeters), salt-marsh plants may recover. Although existing salt-marsh plants may be killed by extensive burial, subsequent wind-deflation may lower the fan to intertidal elevations favorable for colonization by high marsh plant species. Recolonization may occur from seeds or by rhizome extension from adjacent, undisturbed stands of salt-marsh vegetation.

While small dunes (less than 1 meter high) may develop from drift-line deposits on washovers of this scale, major additions to the dune line are not possible unless the washover is significantly enlarged by subsequent overwash. Sand supply for dune building, available from the deflation of the washover, is restricted by the small size of the fan. Without sufficient quantities of sand, major new dunes do not form; overwash at this scale plays an insignificant role in overall barrier dynamics and landward migration.

(c) Washover Flats. Major washover areas exhibit a somewhat different means of stabilization than small-scale features. In general, washover flats are subject to overwash for many years, since rhizome invasion from adjacent dunes and salt marshes is not effective in stabilizing a large area rapidly because there is a high ratio of barren area to perimeter. The principal means of colonization of these major features is through the development of dunes from drift lines. The large size washover flats and great depositional thicknesses provide an abundant source of sand to the developing dune line. Since these flats are not rapidly stabilized, overwash frequently occurs depositing new sand between and bayward of developing dunes. New dunes are established toward the bayward edge of large washovers in association with drift lines deposited in arcuate lines by bay-side storm surges and spring tides. Since a large distance (typically 100 to 200 meters) exists between the newly developing dune and the shoreline, onshore winds also contribute to dune building.

After dunes are well established, *Ammophila breviligulata* rhizomes spread seaward colonizing the barren washover. Complete recovery of a washover occurs when the frontal edge of the new dune merges with the adjacent back dunes and the barrier profile is increased above the overwash threshold. Barrier environments are translocated several hundred meters landward in a quantum fashion by means of overwash and subsequent dune recovery with all ecological units retained intact.

III. VEGETATIVE RESPONSE TO OVERWASH

1. Introduction.

The response of sand-dune and salt-marsh vegetation to overwash burial was studied on Nauset Spit-Eastham. Research was divided into three parts: plant community response to overwash, response of individual species to overwash, and colonization of washovers. Initial research plans were designed to compare the response of vegetation on washovers that were created at different times. After the 1978 storm, the direction of the research changed since all three sites chosen for study had been severely overwashed.

Comparisons of species lists for northeast barrier beaches suggest that the vegetation of Nauset Spit-Eastham is representative of typical northeast barrier beach communities during very early stages of succession (Table 4). Thirty-three species were present on this section of the spit in 1977. This compared to 242 species on Plum Island, Massachusetts, (Ahles, 1973) and 117 on Monomoy Island, Massachusetts, (Moul, 1969). Only three well-developed plant communities have been present on the spit since the first aerial photos were taken in 1938--a dune community and high and low marsh communities. A sand road, in use since 1922, devides salt-marsh communities from dune communities along the length of the spit. Two other discernible, early successional communities are present--the drift-line community and the ecotone between the high marsh and dune community. Shrubs, notably *Myrica pensylvanica* (bayberry), *Prunus maritima* (beach plum), and *Rosa rugosa* (salt spray rose), are present on Nauset Spit-Eastham but do not constitute a shrub community. Of the 21 marshes surveyed in a study comparing salt-marsh productivity in New England, Nauset-Eastham ranked seventh (Godfrey and Travis, 1976). Few well-defined communities, low species number, and high productivity are all characteristic of sand-dune or salt-marsh areas that are either very young or highly stressed.

Table 4. Species list for Nauset Spit-Eastham, 1977 and 1978.

Species	Family	Common name	Availability 1977				Availability 1978			
			a[1]	o[2]	r[3]	vr[4]	a[1]	o[2]	r[3]	vr[4]
Agropyron pungens	Poaceae	Quack grass	x				x			
Ammophila breviligulata	Poaceae	American beachgrass	x				x			
Arenaria peploides	Caryophyllaceae	Sandwort		x				x		
Artemisia caudata	Asteraceae	Wormwood	x				x			
Artemisia stelleriana	Asteraceae	Dusty miller	x				x			
Atriplex arenaria	Chenopodiaceae	Pigweed							x	
Atriplex patula	Chenopodiaceae	Orache			x				x	
Cakile edentula	Cruciferae	Sea rocket	x				x			
Convolvulus sepium	Convolvulaceae	Morning glory							x	
Cytisus scoparius	Fabaceae	Scotch broom				x				x
Distichlis spicata	Poaceae	Spike grass			x					
Euphorbia polygonifolia	Euphorbiaceae	Seaside spurge		x			x			
Festuca rubra	Poaceae	Red fescue			x				x	
Hudsonia tomentosa	Cistaceae	False beach heather				x				x
Juncus gerardii	Cyperaceae	Black grass			x					
Lathyrus japonicus	Fabaceae	Beach pea	x				x			
Limonium nashii	Boraginaceae	Sea lavender	x				x			
Myrica pensylvanica	Myricaceae	Bayberry			x				x	
Panicum virgatum	Poaceae	Panic grass			x				x	
Phragmites communis	Poaceae	Common reed grass		x					x	
Plantago maritima	Plantaginaceae	Seaside plantain		x						
Prunus maritima	Rosaceae	Beach plum			x				x	
Puccinellia maritima	Poaceae	Alkali grass	x				x			
Quercus ilicifolia	Fagaceae	Bear oak				x				x
Rhus radicans	Anacardiaceae	Poison ivy			x				x	
Rosa rugosa	Rosaceae	Salt spray rose		x				x		
Rosa virginiana	Rosaceae	Virginia rose			x				x	
Salicornia europaea	Chenopodiaceae	Glasswort		x						
Salicornia virginica	Chenopodiaceae	Glasswort	x				x			
Salsola kali	Chenopodiaceae	Saltwort		x				x		
Solidago sempervirens	Asteraceae	Seaside goldenrod	x				x			
Spartina alterniflora	Poaceae	Salt-marsh cordgrass	x				x			
Spartina patens	Poaceae	Salt-meadow cordgrass	x				x			
Suaeda linearis	Chenopodiaceae	Sea blite		x				x		
Suaeda maritima	Chenopodiaceae	Sea blite		x				x		
Xanthium echinatum	Chenopodiaceae	Cocklebur			x				x	
Yucca filamentosa	Liliaceae	Yucca				x				x

[1]a = abundant.

[2]o = occasional.

[3]r = rare.

[4]vr = very rare.

An almost continuous dune line, with elevations approaching 5 meters in some areas, extended 2.2 kilometers along the spit in 1977. A recent study of dune-building processes on Nauset Spit-Eastham showed that 5-meter-high dunes can form under optimal conditions in only 6 years (Knutson, 1980). In general, community succession in coastal areas is extremely rapid, aided by the nutrient input of salt spray (van der Valk, 1974; Art, 1976). The few species found within an area of rapid succession suggests that environmental pressures maintain plant community development at a very early stage of succession.

A 1977 map of Nauset Spit-Eastham before the 1978 storm is shown in Figure 2. Three washovers were evident along the spit. The dune line was approximately 150 meters wide, backed by a very wide salt marsh at the northern end, which narrowed to the south. The dune line was steeply scarped on the oceanside, and had eroded approximately 140 meters landward in the past 110 years (see Sec. IV). The off-road vehicle path between the high marsh and dune communities had scarped the back barrier dunes preventing the landward expansion of the dune line.

2. Base-Line Data.

a. Introduction. Three sites on Nauset Spit-Eastham in 1977 were chosen that represented different stages of vegetative recovery following overwash. Site 1 washover was created by overwash in 1972, and consisted of a well-developed *Spartina patens* high marsh and the upper elevation edge of a *Spartina alterniflora* low marsh. High, well-vegetated dunes bordered the washover throat. Site 2 first overwashed in September 1976, presenting the opportunity to study the response of vegetation to burial on a very recent washover. Site 3 had not been affected by recent storms, but appeared to be a possible location for future overwash. The dune and marsh communities could be used as a control, unaffected by overwash. Fieldwork was conducted in the summer of 1977 with the intention of following changes in the vegetation on the three washovers over a period of 2 years.

b. Methodology. The vegetation at each site was sampled using a 0.25-meter-square point-intercept board with 25 evenly spaced holes to calculate cover (Fig. 26; Oosting, 1956). Information concerning frequency (species present), cover, and plant density was collected. A plant was considered in the frequency determination if any part of the plant appeared within the double-framed quadrat. Density was determined by the number of axes breaking the sand surface. For fine grasses, density calculations were made using the average of estimates from three researchers. Quadrats were selected within the plots using a mixed, random, or systematic process (Kershaw, 1976).

Quadrats were spaced at 2-meter intervals along transects chosen at random along the base line in order to take into account the belted zones of the salt marsh. The point-intercept board was placed with two fixed points located along a tape measure which defined the sampling transect, so that each quadrat could be relocated for future study. The elevation relative to sea level was determined for each quadrat using a surveyor's level. Time was the only constraint placed on the number of transects sampled. A field map was made of each plot using the 5- by 5-meter flagged elevation grid as a guideline.

Figure 26. Photo of point-intercept board.

The three research sites were subdivided into five plots (see Sec. II). A total of 2,567 quadrats were sampled within the five plots during the summer of 1977. The most extensively covered were the washover throat and fan of site 1. Vegetative changes, followed since 1972 at this site, presented a unique opportunity to study the revegetation of a washover fan. Site 1 has actively overwashed during severe storms and has trapped sufficient sand on sections of the fan surface to attain an elevation above spring high tides and maintain a dune community. Twenty transects 100 meters long were sampled at site 1 throat for a total of 1,020 quadrats. Twenty-eight transects 50 meters long were established at site 1 fan; a total of 728 quadrats were sampled. Notes were made to indicate which quadrats were located in areas affected by overwash and which were located on the adjacent salt marsh. Nine transects were set at site 2, and 234 quadrats were sampled. At site 3, 351 quadrats were sampled in the dunes and 234 quadrats were sampled in the salt marsh along 13 transects. A field map was made of each plot using the 5- by 5-meter flagged elevation grid as a guideline.

c. Analysis of Data.

(1) Site 1 Fan. Site 1 has been studied since it first formed during a severe northeaster in February 1972. The washover consisted of a throat which meandered through the dune line and a small fan-shaped deposit on the

high marsh. Several months after the initial overwash, elevation transects were established across the fan to document sand surface changes and the revegetation process. Test pits dug in the substrate demonstrated that the initial vegetation was similar to the adjacent, nonoverwashed high marsh. Surficial features such as drift lines and emergent vegetation were noted. In 1975 the same transects were resurveyed, and both recovering and newly established vegetation was recorded. A vegetation map of site 1 in 1975 appears in Figure 27. Plants did not recover from the initial sand deposit, and small dunes developed in the location of the 1972 drift lines by 1975 (Fig. 28).

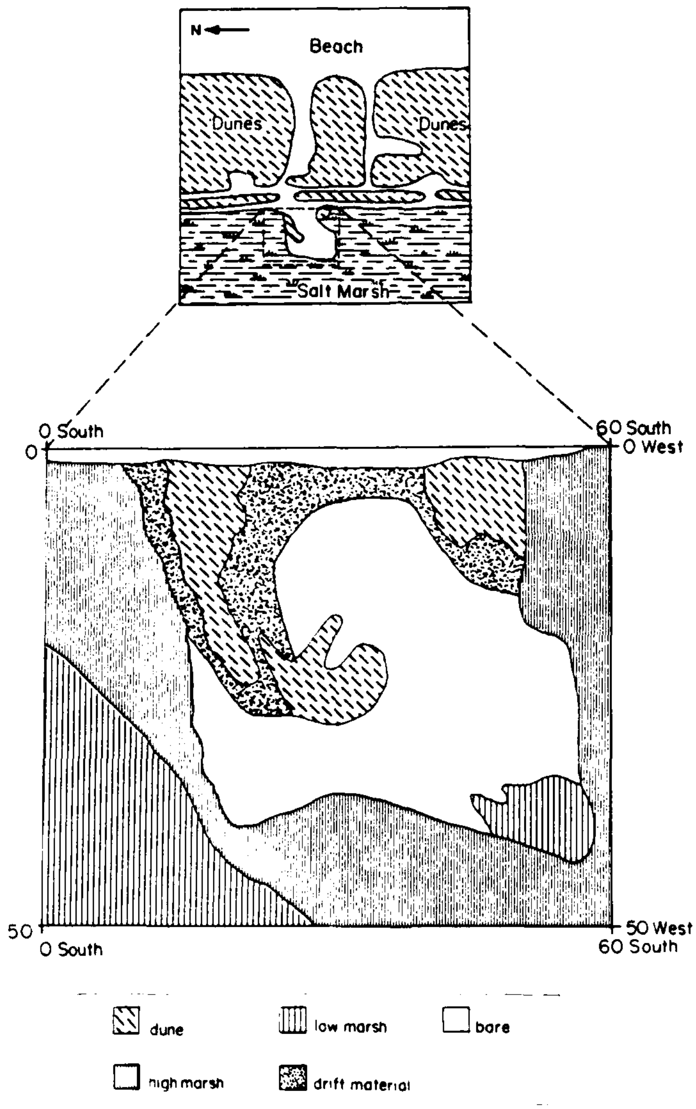


Figure 27. Vegetation map of site 1 fan, 1975.

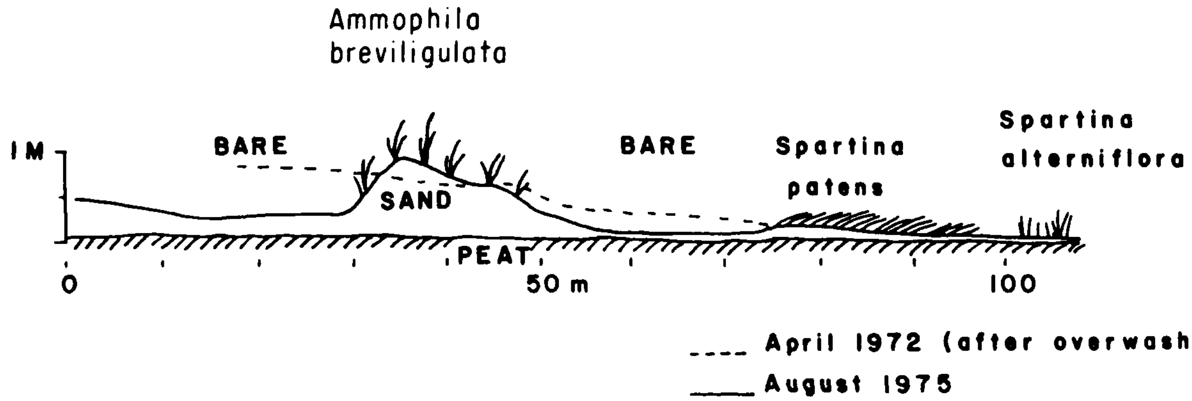


Figure 28. Drift line dune development on a washover fan (after Godfrey, Leatherman, and Zaremba, 1979).

The detailed vegetation study conducted in 1977 increased the available data on washover revegetation. Storms on 10 May and 10 June 1977 flooded the developing dunes, killing many *Ammophila breviligulata* plants. Some new tillers of *Ammophila breviligulata* had recolonized the site by the time the area was sampled in August.

Data from site 1 fan were divided into three sections: the adjacent unaffected marsh, the periphery of the washover, and the center of the washover fan (Figs. 29 and 30). Table 5 reviews the data for the adjacent marsh area. This area was largely high marsh with a mixture of low marsh vegetation at the bayward extremities of the plot. *Spartina patens* was the dominant species, with an importance value (I.V.) of 209.80, indicating that most of the site was within the high marsh community on Nauset Spit-Eastham. *Spartina alterniflora*, *Salicornia virginica* (glasswort), *Puccinellia* sp. (alkaligrass), and *Limonium nashii* (sea lavender), in order of decreasing importance, were the most common components of the low marsh community (Table 5).

Tables 6 and 7 review vegetation data for the peripheral area and the center of the washover fan, respectively. The peripheral area was located at the edge of the fan where sand burial was shallow (<10 centimeters) 5 years after overwash; some plants had grown through the deposit. Other plants colonized this area by rhizome extensions from the adjacent marsh. Species composition of the peripheral area reflected the adjacent marsh vegetation as expected. A comparison of Tables 5 and 6 shows that the species composition for the two areas was very similar. All six plants found in the peripheral area were also found in the adjacent marsh. Only *Distichlis spicata* (spike grass), a minor component of the adjacent marsh, was not present in the peripheral area. These data show that six species are either rhizomatous or capable of withstanding major overwash deposition. *Spartina patens*, *Spartina alterniflora*, and *Salicornia virginica* are rhizomatous. Many marsh plants can withstand some siltation as a natural process occurring in tidal marshes.

The vegetative composition of the center of the washover fan differed greatly from the peripheral or adjacent marsh areas (Table 7). Comparisons of the three areas by I.V. appear in Table 8. *Ammophila*, which cannot withstand saltwater inundation during the growing season, is a good indicator of supratidal vegetation. The other seven species found on the washover fan are also components of the sand-dune community in New England. Only *Spartina patens*

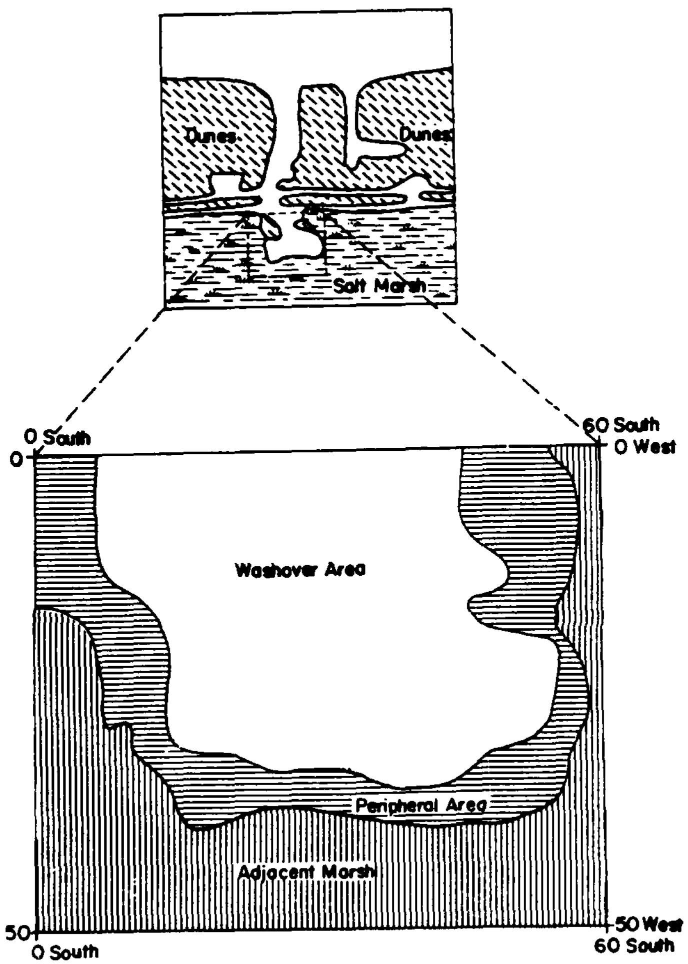


Figure 29. Subdivisions of site 1 fan, 1977 (pre-1978 overwash).

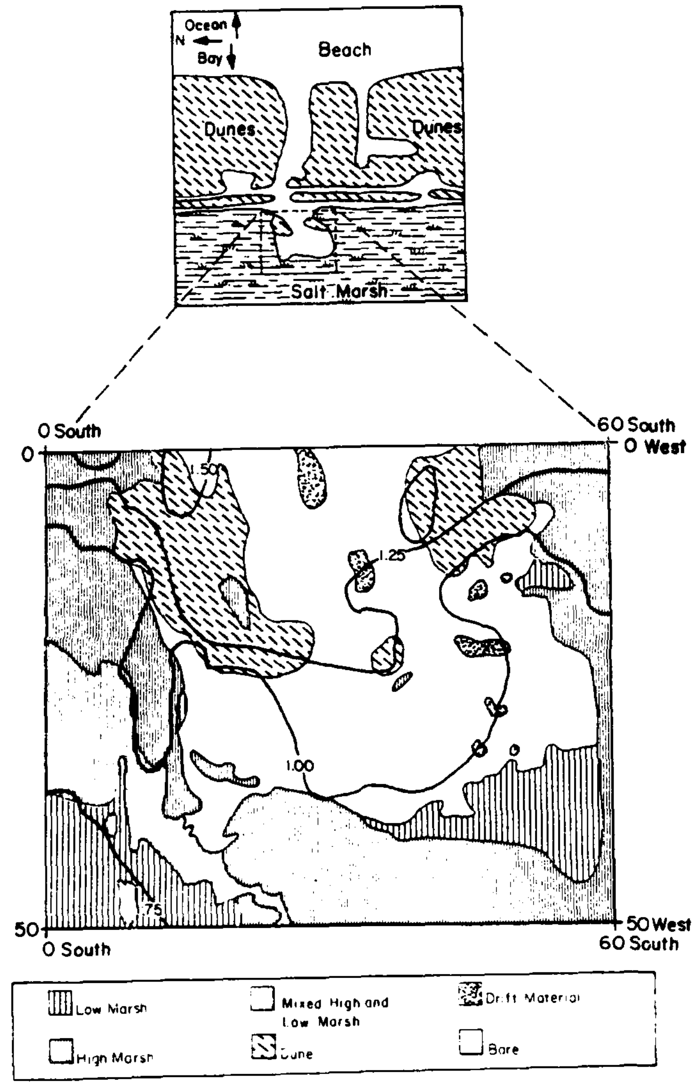


Figure 30. Vegetation map of site 1 fan, August 1977.

Table 5. Summary of quadrat data for the marsh adjacent to site 1 fan washover, 1977.

Species	Frequency		Cover		Density		I.V.[1]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	0.7	0.3	<0.1	<0.1	40	<0.1	0.4
Distichlis spicata	0.7	0.3	<0.1	<0.1	75	<0.1	0.4
Limonium nashii	16.4	7.4	0.4	0.4	115	0.1	7.9
Puccinellia sp.	24.4	11.1	1.6	1.7	3,003	1.2	14.0
Salicornia virginica	38.2	17.3	2.5	2.6	5,488	2.2	22.2
Spartina alterniflora	43.6	19.8	18.6	19.4	6,878	2.8	42.1
Spartina patens	89.5	40.6	72.3	75.6	228,827	93.6	209.8
Bare sand	62.9		10.7				
Drift	21.1		2.3				

[1]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Table 6. Summary of data collected from 150 quadrats sampled at the washover periphery, August 1977.

Species	Frequency		Cover		Density		I.V.[1]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	0.6	1.3	<0.1	0.1	9	<0.1	1.4
Limonium nashii	0.3	0.6	---	---	1	<0.1	0.6
Puccinellia sp.	3.3	7.7	0.9	2.1	230	0.6	10.4
Salicornia virginica	1.7	3.9	0.1	0.3	90	0.2	4.3
Spartina alterniflora	8.5	19.9	5.9	14.2	866	2.2	36.3
Spartina patens	28.7	66.7	34.7	83.4	38,437	97.0	247.1
Bare sand	38.8		51.9				
Drift	18.2		6.5				

[1]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Table 7. Summary of data collected from 303 quadrats sampled on the supratidal washover at site 1 fan, August 1977 (pre-1978 overwash).

Species	Frequency		Cover		Density		I.V.[1]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	0.7	3.3	<0.1	1.2	9	2.8	7.3
Ammophila breviligulata	11.2	57.4	0.6	53.7	106	33.0	144.4
Artemisia caudata	0.3	1.6	<0.1	1.2	8	2.5	5.4
Artemisia stelleriana	0.3	1.6	<0.1	2.4	---	---	2.8
Cakile edentula	1.3	6.6	<0.1	3.7	2	0.6	10.8
Lathyrus japonicus	0.3	1.6	---	---	---	---	2.0
Salsola kali	0.3	1.6	---	---	---	---	2.0
Spartina patens	5.3	26.2	0.4	37.8	60.1	---	124.2
Bare sand	97.1		82.1				
Drift	66.7		16.9				

[1]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Table 8. Comparative importance values at site 1 fan subdivisions, 1977.

Species	Adjacent marsh	Peripheral area	Washover fan	Total
Agropyron pungens	0.4	1.4	7.3	0.6
Ammophila breviligulata	----	----	144.4	4.7
Artemisia caudata	----	----	5.4	0.1
Artemisia stelleriana	----	----	2.8	0.1
Cakile edentula	----	----	10.8	0.5
Distichlis spicata	0.4	----	----	0.3
Lathyrus japonicus	----	----	2.0	0.1
Limonium nashii	7.9	0.6	----	6.0
Puccinellia maritima	14.0	10.4	----	12.5
Salicornia virginica	22.2	4.3	----	17.7
Salsola kali	----	----	2.0	0.1
Spartina alterniflora	42.1	36.3	----	39.4
Spartina patens	209.8	207.1	124.2	215.3

var. *monogyna* and *Agropyron pungens* (quack grass) appeared in all three areas: these two species are capable of growing on low dunes subject to periodic tidal flooding. All plants on site 1 washover fan originated from regeneration of plant fragments or from seed. None of these species originated from the regrowth of plants below the washover fan. Seedlings of *Spartina patens*, *Salsola kali* (saltwort), *Lathyrus japonicus* (beach pea), and *Cakile edentula* (sea rocket) were noted on the fan in 1977; plant fragments of *Ammophila breviligulata* and *Artemisia stelleriana* (dusty miller) were also found on the washover.

(2) Site 1 Throat. Site 1 throat had not been subject to a major overwash since 1972. Occasionally during the winter, swashes overtopped the berm crest, depositing drift material in the washover throat. Site 1 throat showed signs of vegetative recovery by means of rhizome extension from established dunes and by colonization from overwash drift lines. A map of site 1 throat appears in Figure 31. (Elevation data were not collected between transects 9S and 24S from 60 to 100 meters west.) Very sparse drift-line vegetation dominated by *Ammophila breviligulata*, *Cakile edentula*, *Artemisia stelleriana*, *Salsola kali*, and *Lathyrus japonicus* occurred throughout the throat among abundant drift material (7.2 percent cover; Table 9). Well-vegetated *Ammophila breviligulata* dunes were located at the northern and southern edges of the site. A very dense stand of *Ammophila breviligulata* grew on the eastern low dune ridge (80 and 90 meters west), which was less densely vegetated with *Ammophila breviligulata*, *Agropyron pungens*, *Spartina patens*, *Artemisia caudata* (wormwood), and *Solidago sempervirens* (seaside goldenrod). A dense stand of *Spartina patens* var. *monogyna* (I.V. = 110.0 for the entire plot) was located in the southwest corner of the plot.

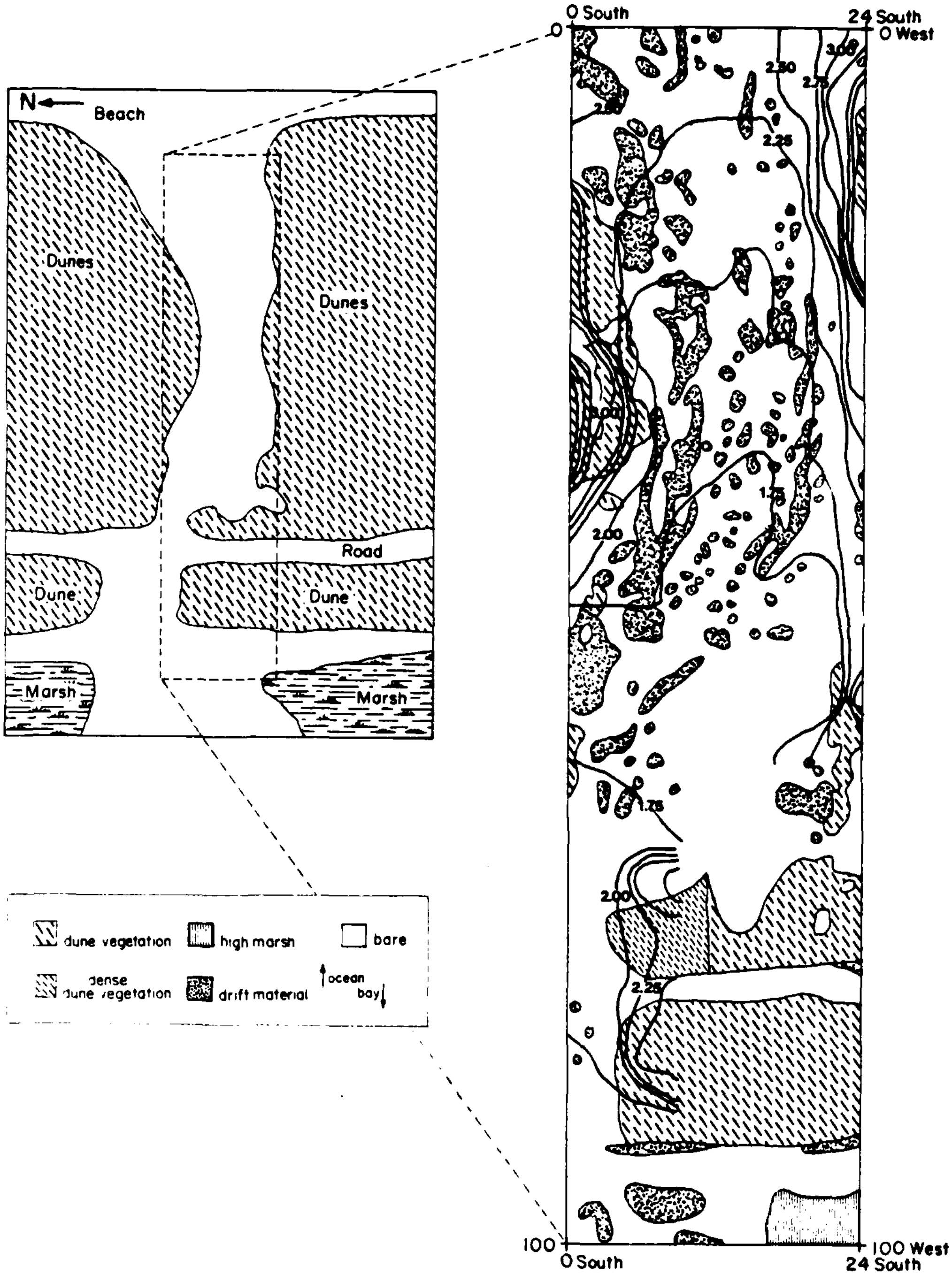


Figure 31. Vegetation map of site 1 throat, August 1977.

Table 9. Summary of data collected from 929 quadrats sampled at site 1 throat, August 1977 (preoverwash).

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	1.4	4.3	0.3	4.5	138	3.6	12.4
Ammophila breviligulata	17.9	53.4	3.1	48.5	1,133	29.8	131.6
Artemisia caudata	0.5	1.5	0.2	2.7	8	0.2	4.4
Artemisia stelleriana	1.8	5.3	0.4	5.6	199	5.2	16.1
Cakile edentula	0.9	2.8	<0.1	0.2	28	0.7	3.7
Euphorbia polygonifolia	0.2	0.6	<0.1	0.2	3	0.1	0.7
Lathyrus japonicus	1.8	5.3	0.1	1.0	24	0.6	6.9
Salsola kali	0.7	2.2	0.1	0.7	5	0.1	3.0
Solidago sempervirens	1.7	4.9	0.3	4.5	22	0.6	10.0
Spartina patens	6.6	19.8	2.1	32.2	2,249	59.0	110.0
Bare sand	99.9		86.5				
Drift	54.9		7.2				

[1]Diversity = 0.6754; Richness = 10.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

(3) Site 2. On 2 September 1976 during a spring tide, a distant tropical storm produced large swells, resulting in overwash at site 2 with sand penetration to the lee of the dune line. Plants were not found on the washover in 1977, except at the fan edges where sand burial was shallow. The adjacent salt marsh was populated with a patchwork growth of high and low marsh vegetation due to irregular topography caused by mosquito ditching.

Vegetation data for site 2 appear in Table 10. Similar to site 1, site 2 was dominated by *Spartina patens* with an I.V. of 137.8, indicating a high marsh community. The distribution of other species is, however, far more uniform than at site 1 fan. There is a mixture of low marsh vegetation among stands of *Spartina patens*. A map of the site shows the sporadic zonation patterns (Fig. 32).

Table 10. Summary of data collected from 234 quadrats sampled at site 2, August 1977 (preoverwash).

Species	Frequency		Cover		Density		I.V.[1]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	8.1	5.6	2.3	3.8	1,168	1.1	10.5
Distichlis spicata	0.4	0.3	0.1	0.1	22	<0.1	0.4
Juncus gerardi	6.8	4.7	<0.1	5.5	9,452	8.4	18.6
Limonium nashii	4.3	2.9	<0.1	<0.1	10	<0.1	3.0
Puccinellia sp.	12.8	8.8	2.2	3.5	5,835	5.2	17.5
Salicornia europaea	1.3	0.9	0.1	0.1	19	<0.1	1.0
Salicornia virginica	43.6	29.8	12.5	20.6	30,111	26.8	77.2
Spartina alterniflora	23.9	----	9.7	16.1	5,835	5.2	37.7
Spartina patens	44.4	30.4	30.4	50.2	64,063	57.2	137.8
Suaeda maritima	0.4	0.3	<0.1	<0.1	1	<0.1	0.3

[1]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

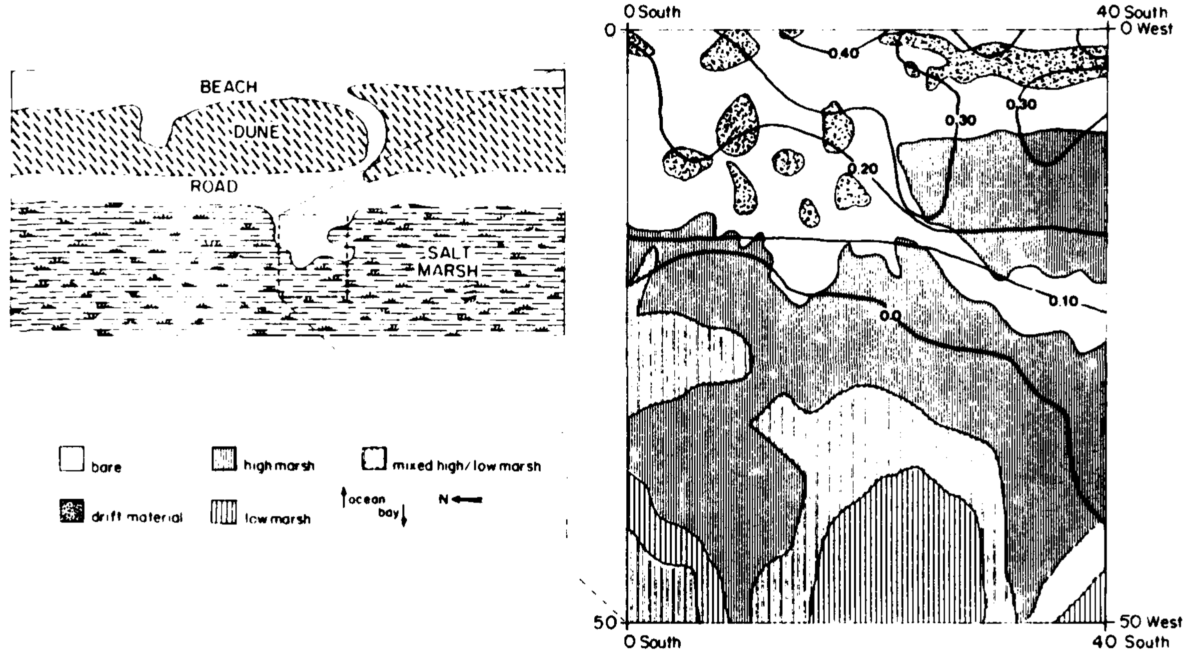


Figure 32. Vegetation map of site 2, August 1977.

(4) Site 3 Throat. At site 3 a small breach (15 meters) in the dune line had been opened during the 10 May 1977 northeaster, killing the *Ammophila breviligulata* that was flooded by saltwater. Overwash surges penetrated into the dune line depositing a small amount of sand in low-lying areas. The vegetation of site 3 throat consisted primarily of stable dune community species dominated by *Artemisia stelleriana* with a dense stand of *Ammophila breviligulata* along the back margin of the dune between 40 to 50 meters (Fig. 33). The western edge of the dune line was steeply scarped by vehicles along the high sand road.

Vegetation data for site 3 throat appear in Table 11. Site 3 throat was similar to site 1 throat, but the distribution and abundance of their component species were very different. *Ammophila breviligulata* was a major component (I.V. = 97.3), but *Artemisia stelleriana* was the dominant species (I.V. = 161.7); *Spartina patens* var. *monogyna* was only a minor element (I.V. = 0.5).

(5) Site 3 Marsh. Site 3 marsh was chosen both as a control, unaffected by overwash, and as a marsh likely to be overwashed in the near future. Unlike site 1 fan and site 2, site 3 marsh had an even mixture of high and low marsh vegetation; this undisturbed site was at the transition between the two communities (Fig. 34). *Spartina patens* (I.V. = 133.1) was the dominant species (Table 12), but *Salicornia virginica* (I.V. = 80.9) and *Puccinellia* sp. (I.V. = 45.9) were found in large numbers only at site 3 marsh in areas sampled on Nauset Spit-Eastham.

3. Community Response to Overwash.

a. Introduction. Plant community response to overwash burial has been studied along the Outer Banks of North Carolina by several investigators. By comparing biomass samples in areas affected by overwash with areas unaffected

Figure 33. Vegetation map of site 3 throat, August 1977

Table 11. Summary of quadrat data collected at site 3 throat, August 1977 (preoverwash).

Species	Frequency		Cover		Density		I.V.[1]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	0.9	0.5	0.1	0.3	53	0.6	1.4
Ammophila breviligulata	62.1	39.4	13.6	45.0	1,237	12.9	97.3
Artemisia caudata	1.1	0.7	0.3	1.0	27	0.3	2.0
Artemisia stelleriana	55.8	35.4	13.0	43.0	7,964	83.3	161.7
Cakile edentula	5.4	3.4	0.3	0.8	19	0.2	4.4
Cyperus polystachyos	0.3	0.2	----	----	19	0.2	0.4
Euphorbia polygonifolia	0.3	0.2	----	----	1	<0.1	0.2
Lathyrus japonicus	19.9	12.6	1.6	5.3	92	1.0	18.9
Rhus radicans	0.3	0.2	<0.1	<0.1	5	0.1	0.3
Solidago sempervirens	11.4	7.2	13.3	4.4	123	1.3	12.9
Spartina patens	0.3	0.2	<0.1	0.1	19	0.2	0.5
Bare sand	97.2		58.5				
Drift	76.9		13.6				

[1]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

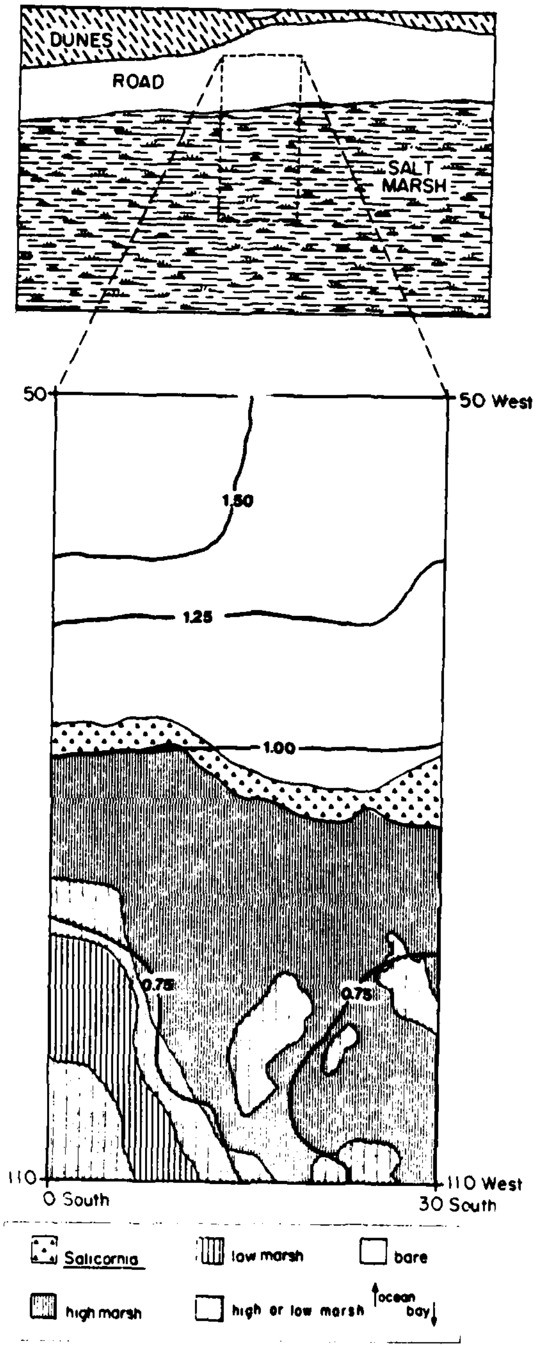


Figure 34. Vegetation map of site 3 marsh, August 1977.

Table 12. Summary of data collected from 351 quadrats sampled at site 3, August 1977 (preoverwash).[1]

Species	Frequency Pct	Frequency Relative	Cover Pct	Cover Relative	I.V.[2]
Limonium nashii	19.2	7.9	1.4	1.3	18.4
Plantago maritima	15.8	6.5	2.6	2.4	18.4
Puccinellia sp.	43.2	17.7	14.2	12.9	45.9
Salicornia virginica	74.8	30.7	25.6	23.2	80.9
Spartina alterniflora	10.7	4.4	5.0	4.5	13.4
Spartina patens	80.3	32.9	61.4	55.8	133.1

[1]Density not sampled.

[2]I.V.'s are adjusted sums of relative frequency and relative cover.

by overwash, Godfrey and Godfrey (1973) showed that southern barrier flat communities dominated by *Spartina patens* are able to recover to initial biomass levels within 1 year. Aerial photographic comparison was used to substantiate these short-term field measurements. Godfrey and Godfrey (1973) suggested that a southern barrier flat community is, in fact, an overwash subclimax community--a community maintained by overwash pressures. Aerial photos and field observations of plant communities to the lee of artificially maintained *Ammophilia* dunes of Cape Hatteras supported the subclimax theory (Dolan, Godfrey, and Odum, 1973). Vegetation not adapted to overwash burial (shrubs) displaced the *Spartina patens*-dominated grassland community after overwash pressure was removed.

Hosier (1973), using a quadrat sampling technique before and after a small overwash (<18 centimeters of sand deposition), showed that overwash burial reduced biomass, but maintained similar plant communities, provided the overall changes in elevation were not dramatic. Travis (1976), also using a quadrat technique, showed that statistical differences in the vegetation 1 year after overwash did not exist between the affected area and an adjacent area that had not recently been overwashed but was subject to frequent overwash activity. Elevation changes of 30 centimeters or greater lead to increases in the water-table height and associated changes in the plant community structure. More recently, using aerial photographic analysis, Hosier and Cleary (1977) showed that a cyclic sequence of overwash community types and physiographic features can be distinguished along some areas of the North Carolina coast.

b. Methodology. To determine plant community response to overwash burial on a northeast barrier beach, two approaches were used. First, the three sites sampled on Nauset Spit-Eastham in 1977 were divided into community types and analyzed based on the range of overwash effects on each community caused

by the 1978 storm. In this analysis, comparisons were made between areas sampled before and after overwash burial. In a second analysis, all data collected on Nauset Spit-Eastham in 1977 and 1978 were again subdivided into plant community types, but were analyzed as a unit using a two-dimensional ordination technique. In this way, salt-marsh and dune communities were spatially separated and postoverwash communities were associated with either the salt marsh or dune end-points of a gradient of community types.

Data collected during 1977 and 1978 on Nauset Spit-Eastham were subdivided to analyze the community response to major overwash sand burial on a north-east barrier beach. For analysis, the communities were divided into three groupings: dune, washover, and salt-marsh (Fig. 35). Whenever possible, quadrats sampled in 1977 were compared with the exact same quadrats resampled in 1978.

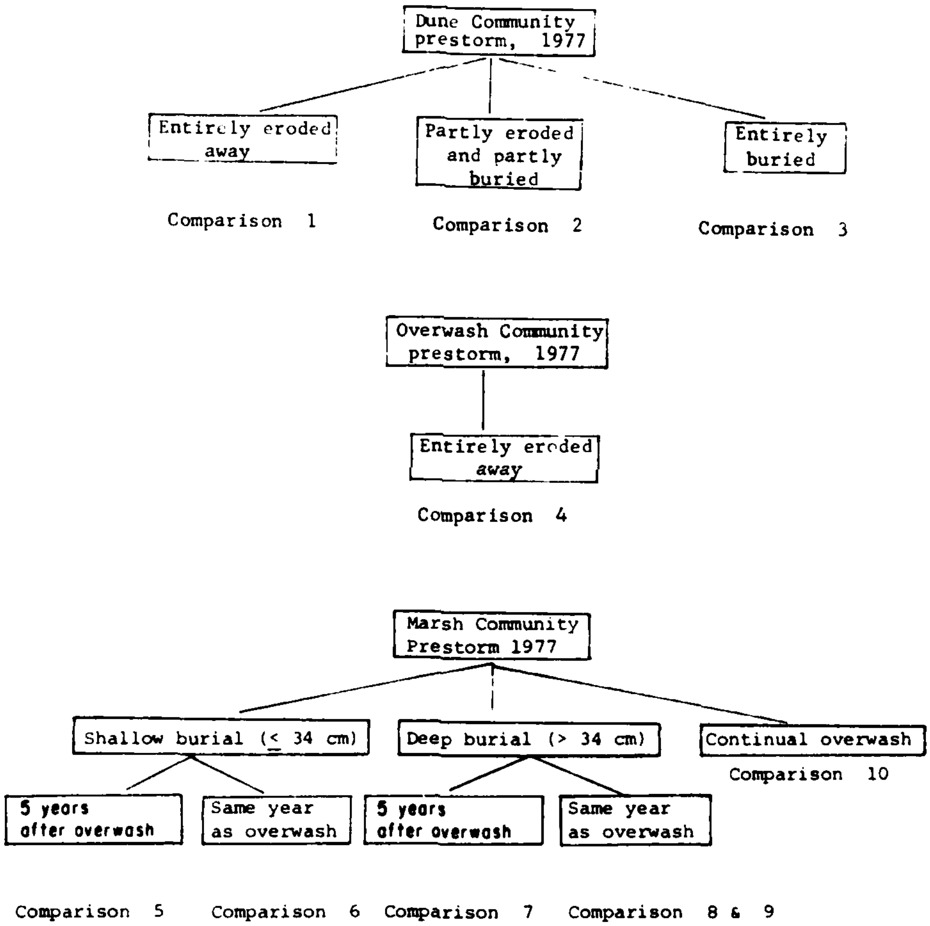


Figure 35. Community analysis: the effects of overwash processes on dune, washover, and salt-marsh communities.

Three types of overwash were analyzed for sand-dune communities (see Fig. 35): dunes completely eroded by overwash surges (comparison 1), dunes entirely affected by overwash activity--partly eroded and partly buried (comparison 2), and dunes that were not eroded but were buried by washover sand (comparison 3). In all three comparisons, quadrats sampled in 1977 were compared with the same quadrats resampled in 1978.

A 1977 washover that was buried by additional washover sand in 1978 was analyzed (Fig. 35, comparison 4). Small dunes had developed on this washover, which were sampled in 1977 and subsequently eroded in February 1978. Quadrats sampled in 1977 were compared to the same quadrats in 1978.

Six comparisons were made for salt-marsh communities (Fig. 35). Two of these comparisons involved mixed high or low marsh areas that were subject to shallow burial which allowed regrowth from below the fan surface during the first year (comparisons 5 and 6). In comparison 5, quadrats sampled in 1978 in areas of site 1 fan that were buried by less than 34 centimeters were compared with the same quadrats before overwash. Quadrats on a 5-year-old washover were compared with quadrats from an adjacent, unaffected area in comparison 6. Three comparisons were made between preoverwash and postoverwash surveys of marshes that had been buried by more than 34 centimeters of washover sand. In two of these analyses, 1977 data were compared with 1978 data; the third comparison used 1977 data on an area initially overwashed in 1972. The final analysis compared a mixed high and low salt marsh to the same area after overwash in February 1978. This area continued to overwash during spring tides until July (comparison 10). Quadrats sampled in 1977 were compared with the same quadrats resampled in 1978.

For each comparison, vegetation data tables were compiled per site, indicating relative frequency, cover, density, and I.V. for each species. The species diversity was calculated using the Simpson index (Simpson, 1949), which is weighted for more common species. A similarity index was calculated comparing the two sites, using a modification of the Gleason similarity index (Gleason, 1920).

$$\text{Gleason index} = \frac{2W}{a + b}$$

where W is the sum of the least relative covers of species held in common between the two plots. W is multiplied by 2 because this cover calculation occurs in both plots; a and b are the sum of the total cover values for each plot. Importance values were used rather than relative cover in order to take advantage of the more detailed data collected. Using the elevation points surveyed in 1977 and 1978 for each site, means, standard deviation, and ranges were calculated for elevation and sand deposition. Whenever appropriate, individual species were compared between sites using the Kruskal-Wallis test, a modified t-test for nonparametric data (Kruskal and Wallis, 1952; Dixon, 1977). The Kruskal-Wallis test ranks data for each treatment and compares each level of the ranking.

A two-dimensional ordination of all vegetation data collected on Nauset Spit-Eastham during 1977 and 1978 was constructed using a method developed by Beals (1960). Vegetation data were divided into 13 plot groupings in 1978 so all sampled quadrats were included only once. Descriptions of the 13 sites used for the ordination appear in Table 13. A matrix of similarity indexes for all sites was constructed using the modified Gleason index used in the site comparisons (Table 14).

Table 13. Review of plots used in two-dimensional ordination of community data.

Plot abbr.[1]	Plot description
1-F-w-77	Supratidal washover fan of site 1 in 1977.
1-F-m-77	Marsh area adjacent to the washover at site 1 fan in 1977.
1-F-p-77	Peripheral area of site 1 fan in 1977.
1-F-s-78	Supratidal area of the washover at site 1 in 1978.
1-F-p-78	Area of site 1 fan (1978) that was marsh in 1977 and received less than 0.34 of washover sand deposition.
1-T-77	Site 1 throat in 1977.
1-T-78	Site 1 throat in 1978.
2-m-77	Marsh adjacent to the washover at site 2 in 1977.
2-p-77	Washover fan and peripheral area at site 2 in 1977.
3-T-77	Site 3 throat in 1977.
3-M-77	Site 3 marsh in 1977.
3-T-78	Site 3 throat in 1978.
3-F-78	Site 3 marsh in 1978.

[1] F = fan; w = washover; m = marsh adjacent to a washover; p = area peripheral to a washover; s = supratidal section of a washover; T = throat; M = marsh.

Table 14. Matrix of similarity indexes used for the two-dimensional ordination.

	Dissimilarity index												
Plot abbr.[1]	3-T-77	3-M-77	2-p-77	2-m-77	1-T-77	1-F-w-77	1-F-p-77	1-F-m-77	3-T-78	3-M-78	1-T-78	1-F-s-78	1-F-i-78
3-T-77	----	0.2	0.6	0.6	46.0	36.8	0.6	0.3	76.2	47.7	36.3	55.1	0.2
3-M-77	99.8	----	45.5	80.3	37.0	41.4	53.9	63.5	0.0	0.0	8.7	15.3	48.8
2-p-77	99.4	54.5	----	49.0	39.9	38.2	39.9	43.2	0.0	0.0	8.7	15.3	35.8
2-m-77	99.4	19.7	51.0	----	40.1	43.9	63.6	71.6	0.0	0.0	8.7	15.3	59.2
1-T-77	54.0	63.0	60.1	59.1	----	88.2	37.5	37.2	56.1	47.9	55.9	56.5	37.0
1-F-w-77	63.2	58.6	61.8	56.1	11.8	----	41.8	42.2	48.0	41.6	56.8	52.6	41.4
1-F-p-77	99.4	46.1	60.1	36.4	62.5	58.2	----	87.3	0.0	0.0	8.7	15.3	80.0
1-F-m-77	99.7	36.5	56.8	28.4	62.8	57.8	12.7	----	0.0	0.0	8.7	15.3	0.0
3-T-78	23.8	100.0	100.0	100.0	43.9	52.0	100.0	100.0	----	62.0	48.3	55.3	0.0
3-M-78	52.3	100.0	100.0	100.0	52.1	58.4	100.0	100.0	38.0	----	40.0	47.5	0.0
1-T-78	63.7	91.3	91.3	91.3	44.1	43.2	91.3	91.3	51.7	60.0	----	40.8	8.7
1-F-s-78	44.9	84.7	84.7	84.7	43.5	47.4	84.7	84.7	44.7	52.5	59.2	----	15.3
1-F-i-78	99.8	51.2	64.2	40.8	63.0	58.6	20.0	100.0	100.0	100.0	91.7	84.7	----

Similarity index

[1] T = throat; M = marsh; p = area peripheral to a washover; m = marsh adjacent to a washover; F = fan; w = washover; s = supratidal section of a washover; i = intertidal washover.

c. Analysis of Data.

(1) Dune Communities.

(a) Comparison 1. All 1,020 quadrats sampled at site 1 throat in 1977 (1-T-77) were compared with the same quadrats sampled in 1978 (1-T-78) to determine the effect of overwash on a dune community that was removed by erosion. Site 1 throat consisted of the washover throat with adjacent dunes (Fig. 31). Cover data in 1977 show that the area was 86 percent bare sand (Table 9). The edges of the throat were principally populated with *Ammophila breviligulata* (I.V. = 131.6) through the dunes and *Spartina patens* var. *monogyna* (I.V. = 110.0) toward the sand road. The I.V. of *Spartina patens* was high because individual tillers grow more densely than any other plant on Nauset Spit-Eastham.

Only three quadrats sampled at site 1 throat were not eroded during the February storm. The mean elevation of site 1 throat was raised only 4 centimeters, but the elevation range was lowered from 2.98 centimeters to 1.65 centimeters. Dunes were flattened (maximum elevation = 4.14 meters above mean sea level (MSL) for 1977, versus 3.32 meters above MSL for 1978), and low areas were filled (lowest elevation = 1.16 meters above MSL for 1977, versus 1.67 meters above MSL for 1978). Mean net depth of sand burial was 0.11 meter (±0.32 meter) for the entire site. Only 13 quadrats were vegetated in 1978 versus 324 quadrats in 1977 (Tables 9 and 15). Species richness was reduced from 10 species in 1977 to 3 species in 1978. Species diversity was dramatically reduced from 0.6754 in 1977 to 0.0582 in 1978.

Table 15. Summary of data collected from 969 quadrat samples at site 1 throat, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Ammophila breviligulata	1.2	80.0	0.1	97.2	54	85.7	262.9
Solidago sempervirens	0.1	6.7	0.1	2.8	1	1.6	11.1
Spartina patens	0.2	13.3	---	---	8	12.7	26.0
Bare sand	100.0		99.8				

[1]Diversity = 0.0582; Richness = 3.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Ammophila breviligulata and *Spartina patens* were codominants in 1977; but only *Ammophila breviligulata* was dominant in 1978. *Spartina patens* and *Solidago sempervirens* were found in quadrats that recovered from overwash burial in 1978. Since the velocity of overwashing surges was greater at site 1 throat than in other areas not bordered by high dunes, only large drift material was deposited in the washover throat. *Ammophila breviligulata* rhizomes and tillers regenerated in these drift piles. *Cakile edentula* was the only other species found in the area. In all cases there was a statistically significant decrease in both cover and density for each species in 1978 compared with 1977. In the site 1 throat comparison, an established dune community was replaced by scattered plants found in drift piles on the washover surface. The high similarity index (55.9) shows the high I.V. of *Ammophila breviligulata* in all supratidal areas on Nauset Spit-Eastham.

(b) Comparison 2. All quadrats sampled at site 3 throat in 1977 (3-T-77) were compared with the same quadrats sampled in 1978 to determine the effect of overwash on a dune that had been eroded in some areas and buried by washover deposits in other areas (Tables 11 and 16). Site 3-T-77 was a well-developed, stable dune area (Fig. 33). A high foredune had cut off most of the area from windblown sand. Many dead *Ammophila breviligulata* (I.V. = 97.3), once more abundant, had in recent years been replaced by *Artemisia stelleriana* (I.V. = 161.7) as the most important plant species. The landward edge of the dune was populated with a dense stand of *Ammophila breviligulata*. A total of 214 sampled quadrats were eroded during the 1978 storm; 152 quadrats were buried by between 1 and 98 centimeters of sand. The mean elevation for the site was raised 15 centimeters, and as at site 1 throat, the elevation ranges were severely truncated from a range of 2.10 to 0.69 meter. Mean net depth of sand burial was 0.30 meter (±0.24 meter).

Table 16. Summary of data collected from 351 quadrat samples at site 3 throat, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Ammophila breviligulata	57.0	48.1	3.3	47.1	384	38.6	133.8
Artemisia stelleriana	10.8	21.2	1.7	24.7	490	49.3	95.2
Cakile edentula	1.7	3.4	0.2	2.1	1	0.1	5.5
Lathyrus japonicus	8.6	16.8	1.0	13.5	90	9.1	39.3
Solidago sempervirens	5.4	10.6	0.9	12.7	30	3.1	26.3
Bare sand	100.0		92.1				
Drift	8.0		0.8				

[1] Diversity = 0.6824; Richness = 5.
[2] I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Vegetative cover was reduced from 28 percent in 1977 to 7 percent in 1978. Species richness was reduced from 11 species in 1977 to 5 species in 1978. Species diversity, however, remained similar between 1977 (0.6075) and 1978 (0.6824). *Ammophila breviligulata*, *Artemisia stelleriana*, *Solidago sempervirens*, and *Lathyrus japonicus*, all of which contributed to the high species diversity in 1977, were either able to recover from overwash burial or were found in drift piles. Although species diversity and the magnitude of the I.V. for each of the major species did not vary greatly between 1977 and 1978, Kruskal-Wallis tests run for each of these species showed that, in all cases, cover and density data were significantly lower in 1978 than in 1977 ($P < 0.01$). *Carex silicea* was eroded by overwash in 1978. *Agropyron pungens*, *Spartina patens*, *Artemisia caudata*, and *Rhus radicans* (poison ivy) did not recover from overwash burial at site 3, but were formerly present in only a few quadrats.

The washover throat of site 3 was not bordered by high dunes, as was the case at site 1. Surges moving through site 3 throat were not restricted to a channel but were spread laterally. Site 3 throat eroded less than site 1 throat due to the lack of flow constriction and prestorm vegetative cover. Drift piles at site 3 had a richer flora than at site 1 throat because fine

organic material and seeds were not carried by overwash surges beyond the area. Site 3 throat drift material contained *Ammophila breviligulata*, *Artemisia stelleriana*, *Lathyrus japonicus*, *Cakile edentula*, and *Salsola kali*. The effect of overwash in a dune area, which was partly eroded and partly buried, is to reduce biomass. The extremely high similarity index (76.2) supports other data that major species relationships are, however, not dramatically altered by overwash.

(c) Comparison 3. The sampled quadrats at site 3 throat that were not eroded in 1978 were compared with the same quadrats sampled in 1977 to determine the effect of overwash on a dune community that had been buried. Vegetation data for this site in 1977 and 1978 appear in Tables 17 and 18. A map of the location of the uneroded dune area is shown in Figure 36. The south and west sides of the area were not eroded. Much of the dense *Ammophila breviligulata* in the 1977 plot was buried. *Artemisia stelleriana* (I.V. = 130.3) and *Ammophila breviligulata* (I.V. = 108.8) were codominants in 1977, with *Lathyrus japonicus* (I.V. = 27.6) and *Solidago sempervirens* (I.V. = 19.3) subdominants. In 1977, 59 percent of the area was vegetated versus 17 percent in 1978. Mean elevation was raised 28 centimeters from 1977 to 1978. Elevation standard deviation comparisons between 1977 (±0.30 meter) and 1978 (±0.12 meter) showed that even affected dunes that remained intact after a major storm were effectively flattened by overwash. Mean sand burial depth in the area was 0.31 meter (σ = 0.14 meter) with a range from 1 to 98 centimeters. Species richness was reduced from 10 to 5 species. Species diversity was high for both years (0.6750 for 1978 and 0.6346 for 1977) and more similar than the comparisons for the entire site 3 throat. All four dominant species were able to recover from substantial overwash burial. Kruskal-Wallis tests were run for cover and density data for all four species. Cover and density for *Ammophila breviligulata* and *Artemisia stelleriana* were significantly reduced ($P < 0.01$) between 1977 and 1978. *Lathyrus japonicus* data were also significantly reduced ($P < 0.05$). There were no significant differences between 1977 and 1978 data for *Solidago sempervirens* ($P > 0.05$). Most of the vegetation in the eroded section of site 3 throat originated from plants recovering from overwash burial. Three quadrats with *Ammophila breviligulata* and three quadrats with *Cakile edentula* were found in drift material among the recovering vegetation. Comparisons of an uneroded dune before and after overwash burial showed that biomass was reduced significantly but that dominant species remained the same. Only minor elements of the original community were eliminated by overwash pressure. A high similarity index (83.6) substantiates the similarity of the buried dune community to the original community.

(2) Drift Communities.

Comparison 4. During the 1977 sampling period, site 1 fan quadrats were divided into three parts: (a) the area unaffected by overwash, referred to as the adjacent marsh area (site 1-F-m-77); (b) the area affected by overwash where no vegetation grew, referred to as the washover area (site 1-F-w-77); and (c) the area where vegetation either grew through the deposit, or where plants from the adjacent marsh were able to colonize by rhizome extension, referred to as the peripheral area (site 1-F-p-77). A map of the subdivisions of site 1 fan in 1977 appears in Figure 29. Quadrats sampled in site 1-F-w-77 were compared with the same quadrats resampled after the February storm in order to determine the effect of overwash on an area that had previously overwashed. Vegetation data for the two sampling periods appear in Tables 7 and 19. Test pits, dug in the fan where vegetation had been present in 1977, demonstrated that all plants on the original washover surface had been eroded by the storm.

Table 17. Summary of data collected from 137 quadrat samples at the site 3 throat section not eroded by overwash, August 1977.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	2.2	1.1	0.3	0.6	53	1.3	3.0
Ammophila breviligulata	78.1	38.1	21.0	51.2	792	19.5	108.8
Artemisia caudata	2.9	1.4	0.8	1.9	27	0.7	4.0
Artemisia stelleriana	56.2	27.4	12.4	30.2	2,944	72.6	130.3
Cakile edentula	8.0	3.9	0.4	0.9	13	0.3	5.1
Euphorbia polygonifolia	0.7	0.4	---	---	1	<0.1	0.4
Lathyrus japonicus	35.1	17.1	3.3	8.1	97	2.4	27.6
Rhus radicans	0.7	0.4	0.1	0.1	5	0.1	0.6
Solidago sempervirens	20.4	10.0	2.8	6.8	102	2.5	19.3
Spartina patens	0.7	0.4	0.1	0.1	19	0.5	1.0
Bare sand	97.8		47.6				
Drift	84.7		15.9				

[1] Diversity = 0.6346; Richness = 10.
[2] I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Table 18. Summary of data collected from 137 quadrat samples at the site 3 throat section not eroded by overwash, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Ammophila breviligulata	51.8	46.1	8.2	48.0	396	40.4	134.5
Artemisia stelleriana	24.1	21.4	4.2	25.0	445	45.4	91.8
Cakile edentula	2.2	2.0	0.2	1.4	---	---	3.3
Lathyrus japonicus	20.4	18.2	2.0	11.9	104	10.6	40.6
Solidago sempervirens	13.9	12.3	2.3	13.8	36	3.7	29.8
Bare sand	100.0		82.9				
Drift	3.6		0.5				

[1] Diversity = 0.6750; Richness = 5.
[2] I.V.'s are importance values calculated from cover, frequency, and density of the plants.

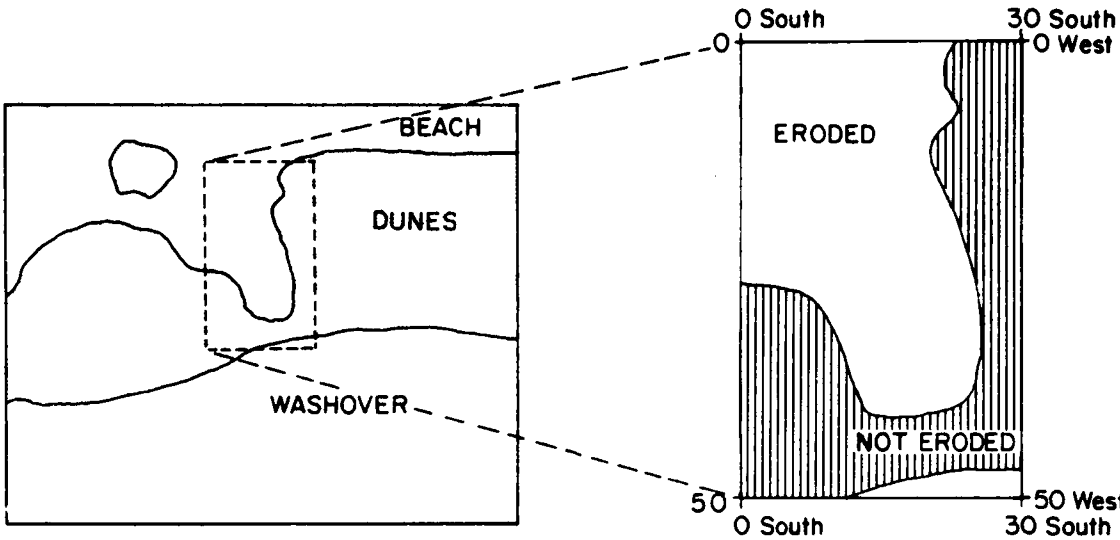


Figure 36. The site 3 throat section not eroded by overwash, February 1978.

Table 19. Summary of data collected from 303 quadrat samples at the site 1 fan section that was a supratidal washover in 1977, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Ammophila breviligulata	2.3	28.0	0.1	24.0	7	17.5	69.5
Artemisia stelleriana	2.0	24.0	<0.1	4.0	3	7.5	35.5
Cakile edentula	0.7	8.0	0.2	56.0	4	10.0	74.0
Euphorbia polygonifolia	0.3	4.0	---	---	1	2.5	6.5
Lathyrus japonicus	1.3	16.0	---	---	6	15.0	31.0
Panicum sp.	0.3	4.0	---	---	0	---	4.0
Spartina patens	1.0	12.0	<0.1	8.0	18	45.0	65.0
Xanthium echinatum	0.3	4.0	<0.1	8.0	1	2.5	14.5
Bare sand	100.0		95.5				
Drift	22.1		3.5				

[1]Diversity = 0.6144; Richness = 8.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

In 1977 the area was sparsely vegetated (bare sand, 99 percent cover). *Ammophila breviligulata* (I.V. = 144.4) and *Spartina patens* (I.V. = 124.2) were the dominant species. The mean elevation of site 1-F-w was raised 72 centimeters between 1977 and 1978. Although site 1-F-w-77 was an embryonic dune area, the relief of the area was greater after the storm (σ = 0.21 meter), since large drift piles were deposited on the washover fan. Of a total of 303 quadrats sampled, 61 quadrats were vegetated in 1977 versus 25 that were vegetated in 1978. Four common drift-line species (*Ammophila breviligulata*, *Lathyrus japonicus*, *Cakile edentula*, *Artemisia stelleriana*) were found in both

the 1977 and 1978 sites. The similarity index (50.0) suggests that the areas are quite similar. Site 1-F-w-77, which first overwashed 5 years earlier, contained species with higher I.V.s that developed after an overwash event (*Agropyron pungens* and *Spartina patens*). Otherwise, the species composition is very similar between 1977 and 1978. The effect of overwash on an area that has recently overwashed is to maintain an early successional drift-line community.

(3) Salt-Marsh Communities.

(a) Comparison 5. Site 1-F-78 was subdivided in order to analyze a salt-marsh community that had recovered from shallow overwash burial. Using sampling data, salt-marsh species were found to recover from as much as 33 centimeters of overwash sand burial. The quadrats at site 1 fan receiving less than 34 centimeters of sand deposition between summer 1977 and August 1978 were also analyzed. These 152 quadrats (site 1-F-p-78) were compared with the same quadrats sampled in 1977 (Tables 20 and 21). A map of the location of these quadrats appears as Figure 37. The area was dominated by *Spartina patens* (I.V. = 192.3) in 1977. Cover information indicated that only 16 percent of the site was unvegetated in 1977. Mean elevation was increased by 17 centimeters between 1977 and 1978. Elevation range and standard deviation were similar in both periods. Species richness was reduced from seven species in 1977 to only two species in 1978. *Salicornia virginica*, *Puccinellia maritima* (alkaligrass), *Distichlis spicata*, and *Limonium nashii* did not recover from shallow overwash burial. The species diversity of the area remained similar from 1977 (0.4784) to 1978 (0.4935), reflecting the high I.V.s of *Spartina patens* and *Spartina alterniflora* for both years. Kruskal-Wallis tests run on *Spartina patens*, *Spartina alterniflora*, and bare sand data showed that cover and density for *Spartina patens* were significantly reduced ($P < 0.01$) between 1977 and 1978; cover for bare sand was significantly increased ($P < 0.01$) between 1977 and 1978, but cover and density of *Spartina alterniflora* were not significantly changed between 1977 and 1978 ($P > 0.05$). The percentage of cover of *Spartina alterniflora* actually increased between 1977 (23 percent) and 1978 (28 percent). The similarity index comparing the two sites is very high (81.6) because *Spartina patens* and *Spartina alterniflora* were effectively able to recover from the shallow overwash burial (less than 34 centimeters deep at this site).

Table 20. Summary of data collected from 152 quadrat samples at the site 1 fan section that supported salt-marsh vegetation in 1977 and was buried by less than 34 centimeters of washover sand, August 1977.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Distichlis spicata	1.3	0.5	0.1	0.2	75	0.1	0.7
Limonium nashii	20.4	8.3	0.8	0.8	91	0.1	9.2
Puccinellia maritima	32.2	13.1	2.0	2.2	1,579	1.3	16.5
Salicornia virginica	42.8	17.3	3.5	3.9	4,040	3.2	24.5
Spartina alterniflora	56.6	22.9	22.8	25.4	5,072	4.1	52.4
Spartina patens	82.9	33.6	60.5	67.5	113,681	91.3	192.3
Suaeda maritima	10.5	4.3	0.1	0.1	39	0.1	4.4
Bare sand	77.0		15.8				
Drift	9.2		0.2				

[1]Diversity = 0.4784; Richness = 7.

[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Table 21. Summary of data collected from 152 quadrat samples at the site 1 fan section that supported salt-marsh vegetation in 1977 and was buried by less than 34 centimeters of washover sand, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Spartina alterniflora	51.3	46.2	28.5	44.3	3,817	11.6	102.1
Spartina patens	59.9	53.9	35.8	55.7	29,040	88.4	197.9
Bare sand	99.3		40.5				
Drift	6.6		2.1				

[1]Diversity = 0.4935; Richness = 2.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

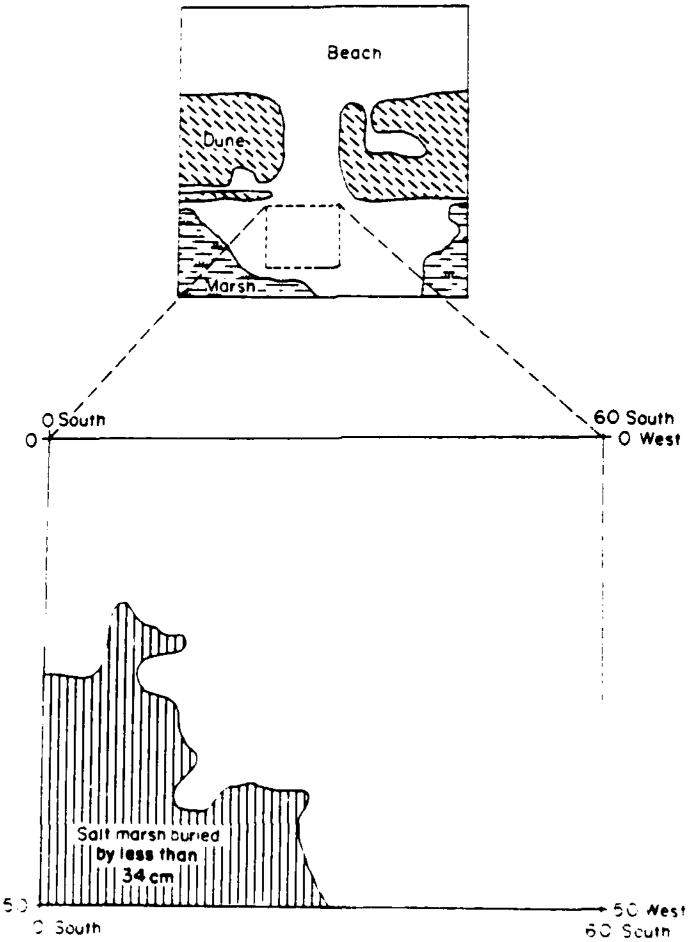


Figure 37. Site 1 fan quadrats that supported salt-marsh vegetation in 1977 and were buried by less than 34 centimeters of washover sand in February 1978.

(b) Comparison 6. Site 1-F-p-77 was affected by overwash in 1972 and had recovered from shallow sand deposition by regrowth from below the fan surface or by rhizome extension from the surrounding marsh. Comparisons were made between this recovery area and the adjacent marsh (site 1-F-m-77), which was unaffected by overwash, to determine the community response to shallow overwash burial 5 years after overwash (Fig. 29; Tables 5 and 6). Test pits dug in the fan after the 1972 storm demonstrated that site 1-F-m-77 vegetation was similar to the vegetation below the washover fan. Mean elevation for site 1-F-p-77 was 17 centimeters higher than the surrounding marsh. Species richness was similar in the two areas (six species at site 1-F-p-77 and seven at site 1-F-m-77). Only *Distichlis spicata* was present on the marsh, but was not found in the peripheral area.

Other vegetation data from Nauset Spit-Eastham suggest that *Salicornia virginica*, *Puccinellia* sp., *Agropyron pungens*, and *Limonium nashii* are not able to recover from substantial burial (greater than 0.10 meter). These species probably colonized the peripheral area after the initial vegetative recovery from overwash burial. Kruskal-Wallis tests run on all cover and density data demonstrated that in all cases there was a significantly lower value for the peripheral area than the adjacent marsh ($P < 0.01$). The high similarity index (87.3) indicates that, after 5 years, peripheral areas of a washover fan affected by shallow burial resemble the surrounding marsh areas.

(c) Comparison 7. All 234 quadrats sampled at site 3-M-77 were compared with the same quadrats resampled in 1978 to determine the effect of deep overwash burial (>0.45 meter) on a salt-marsh community (Tables 12 and 22). Site 3-M-77 was a well-developed salt marsh in 1977 dominated by *Spartina patens* (cover = 61 percent), *Salicornia virginica* (cover = 26 percent), and *Puccinellia* sp. (cover = 14 percent).

Table 22. Summary of data collected from 221 quadrat samples at site 3 marsh, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Ammophila breviligulata	1.4	50.0	<0.1	50.0	2	20.0	120.0
Artemisia stelleriana	0.5	16.7	—	—	1	10.0	26.7
Euphorbia polygonifolia	0.5	16.7	—	—	1	10.0	26.7
Lathyrus japonicus	0.5	16.7	<0.1	50.0	6	60.0	126.7
Bare sand	100.0		95.3				
Drift	37.6		4.2				

[1]Diversity = 0.5000; Richness = 4.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

The entire area was subject to overwash burial (>0.45 meter), which exceeded the recovery capacity of all salt-marsh plants (Table 22). Mean elevation was increased by 68 centimeters from 1977 to 1978 (Fig. 21). Topographic relief was increased between 1977 ($\sigma = 0.08$ meter) and 1978 ($\sigma = 0.19$ meter). Site 3-M-77 was extremely flat, reflecting the gradual sedimentation process in salt marshes (Ranwell, 1959). The February 1978 overwash deposit at site 3-M sloped marshward and contained occasional drift piles, which also increased microtopographic differences.

Salt-marsh plants did not recover from overwash burial that exceeded 45 centimeters. Six salt-marsh species were present in 1977; four drift-line species were present in 1978. Postoverwash vegetation was found in scattered storm-generated drift piles and bay-side drift lines. The similarity index (0.0) emphasized the complete change in plant community composition.

(d) Comparison 8. Site 1-F-78 was subdivided in order to analyze a salt-marsh community that received greater than 34 centimeters of overwash sand burial. Quadrats at site 1 fan that received greater than 34 centimenters of sand and had not eroded were analyzed. A map of the location of these 261 quadrats appears in Figure 38. Vegetation data for these quadrats were compiled for 1977 and 1978 (Tables 23 and 24). The 1977 area was dominated by *Spartina patens* (I.V. = 242.9) with *Spartina alterniflora* (I.V. = 28.7) and *Salicornia virginica* (I.V. = 13.1) as subdominants.

Mean elevation in the area was raised 72 centimeters. As in comparisons 5, 6, and 7, topographic relief was increased from 1977 (σ = 0.19 meter) to 1978 (σ = 0.29 meter). Plants did not recover from overwash burial in excess of 34 centimeters. Six salt-marsh species were present in the sampled quadrats in 1977, while three drift-line species were present in 1978. Postoverwash vegetation was found principally in bay-side drift lines deposited during the late March spring tides. As in comparison 7, the similarity index was 0.0, stressing a complete change in plant community composition in areas receiving deep (>34 centimeters) deposits of sand.

(e) Comparison 9. Quadrats sampled at site 1-F-w-77 were compared with quadrats from site 1-F-m-77 to analyze the effect of deep overwash burial on a salt marsh after 5 years (Tables 5 and 7). The mean elevation of the washover area was 41 centimeters higher than the surrounding marsh. Salt-marsh vegetation did not recover from the initial washover deposit. Only one species, *Spartina patens*, was present at the salt marsh, and also on the washover fan. Aeolian deflation of the surface created a low area where seedlings of *Spartina patens* became established. Kruskal-Wallis tests on cover and density of *Spartina patens* and cover for bare sand showed that there were significant differences between 1977 and 1978 ($P < 0.01$). The high similarity index (42.2) comparing the two areas reflects the growth habit and elevation range of *Spartina patens* and the sparseness of vegetation on recent washovers.

(f) Comparison 10. The 234 quadrats sampled at site 2 in 1977 were compared with the same quadrats resampled in 1978 to illustrate the effect of continual overwash on a mixed high or low marsh community. Site 2 supported a mixed high or low marsh community in 1977 that experienced between 20 and 50 centimeters of overwash deposition during the February storm. The area, however, continued to overwash during spring tides until July. Plants did not recover from overwash burial, although at times during the growing season dead biomass from the 1977 vegetation was exposed. Drift-line vegetation was not present in the area because drift material was not deposited on the washover surface. Drift-line vegetation could not have withstood saltwater inundation during the growing season, even if it had been present.

(4) Ordination of Data. In Figure 39, two distinct groupings are evident in the ordination of data collected on Nauset Spit-Eastham in 1977 and 1978: salt-marsh communities (lower right) and dune communities (upper left). Marshes affected by shallow overwash burial (site 1-F-p-77 and site 1-F-p-78)

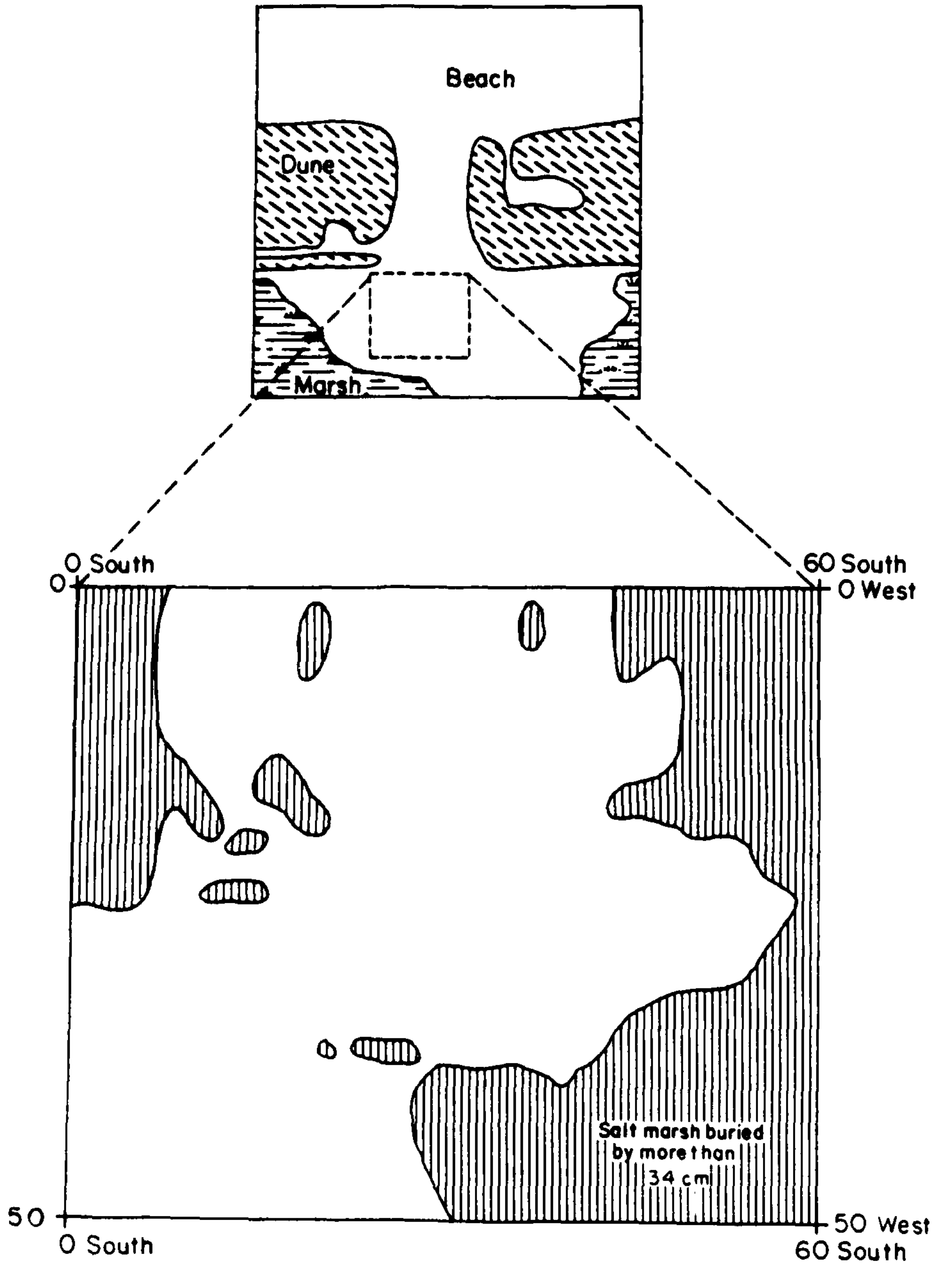


Figure 38. Site 1 fan quadrats that supported salt-marsh vegetation in 1977 and were buried by more than 34 centimeters of washover sand, February 1978.

Table 23. Summary of data collected from 261 quadrat samples at the site 1 fan section that supported salt-marsh vegetation and was buried by more than 34 centimeters of washover sand, August 1977.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Agropyron pungens	0.8	0.5	0.1	0.1	40	<0.1	0.7
Limonium nashii	5.4	3.6	<0.1	0.1	25	<0.1	3.7
Puccinellia sp.	11.1	7.5	0.9	1.2	1,569	1.1	9.8
Salicornia virginica	16.5	11.1	0.7	0.9	1,527	1.1	13.1
Spartina alterniflora	23.0	15.5	8.7	11.5	2,469	1.7	28.7
Spartina patens	90.0	60.6	65.3	86.2	139,635	96.1	242.9
Bare sand	70.5		25.9				
Drift	41.8		6.8				

[1]Diversity = 0.2428; Richness = 6.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

Table 24. Summary of data collected from 261 quadrat samples at the site 1 fan section that supported salt-marsh vegetation in 1977 and was buried by more that 34 centimeters of washover sand, August 1978.

Species[1]	Frequency		Cover		Density		I.V.[2]
	Pct	Relative	Pct	Relative	Total	Relative	
Ammophila breviligulata	1.5	40.0	<0.1	10.0	3	37.5	87.5
Artemisia stelleriana	1.2	30.0	<0.1	40.0	3	37.5	107.5
Cakile edentula	1.2	30.0	0.1	50.0	3	25.0	105.0
Bare sand	100.00		93.68				
Drift	33.71		5.78				

[1]Diversity = 0.6800; Richness = 3.
[2]I.V.'s are importance values calculated from cover, frequency, and density of the plants.

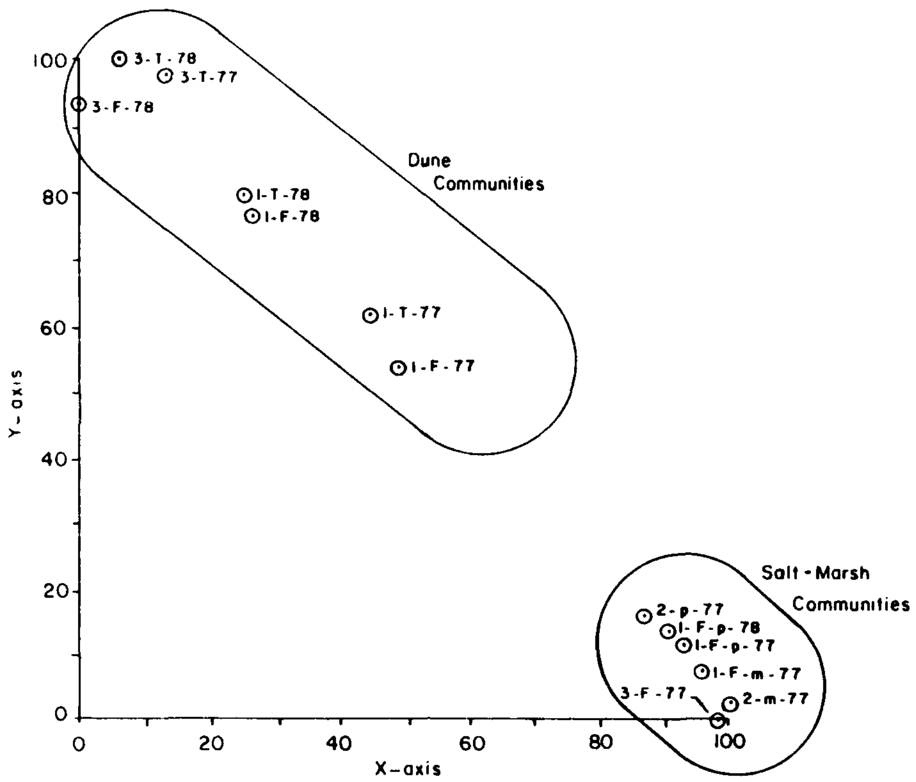


Figure 39. Two-dimensional ordination of Nauset Spit-Eastham vegetation data.

are associated with the salt-marsh grouping; salt marshes affected by deep overwash burial (site 3-F-78, site 1-F-77, and site 1-F-78) are associated with the dune or drift-line grouping. Dunes affected by overwash burial (site 3-T-78 and site 1-T-78) are also associated with the dune or drift-line grouping.

Elevation data for both sites 1 and 3 were tied to a local USGS bench mark so that all site elevations could be compared. Elevation mean and range were calculated for each of the 13 sites and superimposed on the two-dimensional ordination (Fig. 40). With the exception of site 3-F-78, the dune grouping elements are all located at higher elevations than the salt-marsh grouping elements. The effect of overwash on sampled dunes was not only to lower the mean elevation and range for each site, but also to maintain a supratidal elevation capable of sustaining a dune community. In sampled salt marshes that recovered from shallow burial, elevation mean and range were not raised enough to make the sites supratidal. Dune or drift-line vegetation could not withstand inundation, and salt-marsh plants were able to recover. In sampled salt marshes that were buried by more than 34 centimeters of overwash sand, elevation was raised enough to sustain a dune community. The one notable exception is site 3-F-78 which by Nauset Spit-Eastham standards was still within an intertidal range, although an average of 72 centimeters of sand was deposited on the site in 1978. Spring tides that are generally lower during the summer than during the spring and fall enabled dune vegetation to survive at low elevations. During the summer of 1978, there were no major storms so that these low-lying drift lines were not flooded by the high tides. Dune vegetation was able to grow at lower elevations during that summer than in previous years. Most of the plants in site 3-F-78 were killed by saltwater inundation in 1979; a continuous dune community did not form.

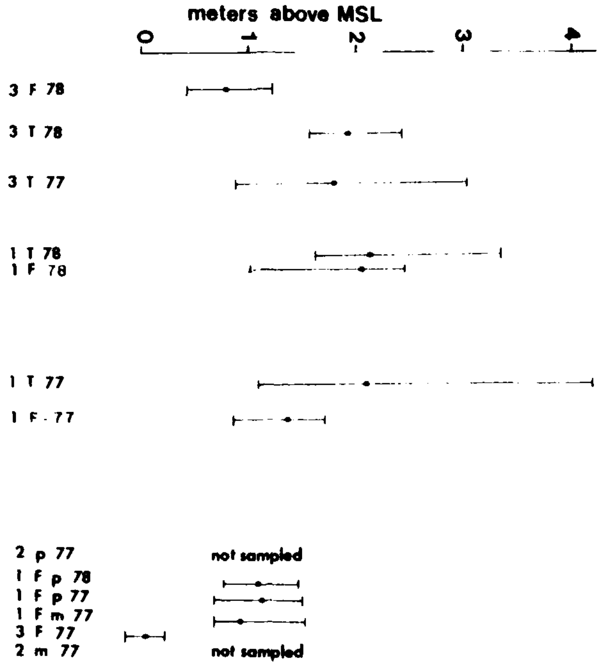


Figure 40. Elevation of sites used in ordination (see Fig. 39).

d. Discussion. Dunes that are eroded during overwash are recolonized by dune vegetation by means of seeds and plant fragments regenerating in drift piles found on washover deposits and by rhizome extension from nearby remnant dunes. In major washover channels through the dune line, few drift piles are found. Drift piles that are deposited in washover throats are principally composed of large material (either shrub fragments or large sections of *Ammophila* rhizomes torn from the dunes), which is difficult for overwash surges to carry through the dune line. *Ammophila breviligulata* is the principal colonizing species. The seedlings are seldom found in drift piles in areas that have been dunes, because overwash surges carry light material through the area toward the fan terminus.

In the few dune areas not eroded by overwash, the poststorm community is very similar in composition to the original community. Increase in *Ammophila breviligulata* biomass has often been highly correlated with increases in the amounts of aeolian sand deposition (Tansley, 1968; Ranwell, 1975; Chapman, 1976). On accreting dunes, vegetation is undergoing selection for genotypes capable of withstanding continual burial. Aeolian sand burial can occur throughout the year when windspeeds exceed threshold values (approximately 24 kilometers per hour), while overwash burial occurs during a single storm. Both depositional processes are, however, more similar at Nauset Spit when seasons are considered. Sustained, high winds and accompanying sand transport are more common during the winter, when dune vegetation is dormant. Aeolian sand deposition of 50 centimeters or greater per year is common in the northeast (Goldsmith, 1972). Dune species, principally *Ammophila*, seem to grow best in the areas of high accretion. Overwash sand deposition in February 1978 also

occurred while dune species were dormant. Deposition did not exceed typical rates of aeolian accretion on dunes. Saltwater accompanying the overwash surges percolated through the highly porous dune sand and was leached by heavy rains accompanying the storm. The species that recovered from overwash burial were the same species commonly found on accreting foredunes.

The season that overwash occurs must play an important role in the dune community response to burial. In May 1977 and again in June 1977, northeasters resulted in overwash at Nauset Spit-Eastham. Overwash surges penetrated the dune line at site 3, creating the small breach and washover that were present in summer 1977. *Ammophila breviligulata* and *Lathyrus japonicus* in site 3 and *Ammophila* in areas south of site 3 were killed wherever flooded by saltwater. The overwash event in September 1976 (that created site 2), however, did not kill flooded *Ammophila*. Young dune plants or dune plants that have recently broken dormancy have tissue that is susceptible to damage from saltwater exposure. Older plants are better able to withstand contact with saltwater. Therefore, overwash burial on a dune community in the early part of the growing season may kill most of the plants. Overwash at other times during the year, however, may not hinder growth and, in fact, may aid in the dune-building process by adding large volumes of sand to existing dunes.

Salt-marsh vegetation on Nauset Spit-Eastham did not grow through washover deposits greater than 33 centimeters deep. In areas where deposition was less than 33 centimeters only *Spartina patens* and *Spartina alterniflora*, the two major plant species in the high and low marsh communities, were able to recover. *Spartina patens* cover and density were significantly reduced by overwash deposition of sand. Cover and density of *Spartina alterniflora* were, however, not reduced in areas receiving shallow burial. *Spartina alterniflora* is the principal plant species in the lower salt marsh, where substantial natural siltation takes place. Annual deposition of silt, as much as 20 centimeters, has been recorded for some British sites (Chapman, 1976). *Spartina alterniflora* is adapted to high siltation rates and may, therefore, be well adapted to recovery from occasional burial from overwash. In all cases, species number in recovering salt-marsh communities is reduced by shallow overwash burial. Species not recovering from overwash burial may, by means of rhizome extension from the surrounding marsh areas or by seedling establishment, recolonize fringe areas of washover features within 5 years of an overwash. The topographic relief in marshes is increased following overwash due to the presence of storm drift piles.

Salt-marsh vegetation that is buried by more than 34 centimeters of washover sand does not recover. Holes dug in the substrate reveal that, in most cases, regrowth is never initiated by plants that do not recover from overwash burial. Species composition in all documented cases completely changed from preoverwash to postoverwash. Topographic relief was increased in marsh areas subject to deep burial. On washovers that are continuously subject to overwash, salt-marsh species do not recover from burial although they may periodically be exposed by such activity.

The three major sites chosen for study on Nauset Spit-Eastham presented a variety of comparisons that could be made between preoverwash and postoverwash communities. Because the areas were located principally in the dunes and in near-dune marshes, certain plant communities were present that would not have been considered if a random selection of sites had been used. Most of the

dunes affected by overwash were completely eroded and the community response resembled that in comparison 1 (Fig. 35). Very few dunes were buried by washover sand, although on a less-developed barrier beach, low dunes would be present and might be buried without erosion. Most salt marshes were buried by deep deposits of sediment, and marsh vegetation did not recover. Vegetation did recover on a few areas near the edge of the washover fans, where sediment had been reworked by the wind and tides.

4. Species Response to Overwash Burial.

a. Introduction. Three types of sedimentation may affect plants on barrier beaches: (1) burial by aeolian sand deposition in dunes during early physical development; (2) burial of salt-marsh species by sand, silt, and organic material carried by floodtides; and (3) burial of all plant species on barrier beaches by overwash. Dune-building processes and the response of the major dune species to aeolian sand deposition have been studied in detail in the United States (Woodhouse, 1978; Knutson, 1979) and in Europe (Phillips, 1975) to aid revegetation and stabilization programs in coastal areas. Nutrient requirements, sand-trapping ability, and optimal planting strategies have been determined for species capable of withstanding continual sand deposition (Woodhouse, Seneca, and Broome, 1976).

Ammophila is one of the most studied of these dune-bulding plants; it has reportedly grown through as much as 1.20 meters of sand accumulated in one growing season (Woodhouse, 1978). Ranwell (1958), in his study on British dunes, stated that while *Ammophila arenaria* (European beachgrass) can recover from at least 0.90 meter of aeolian sand burial in the course of a growing season, it probably cannot recover from an instantaneous burial of that extent. Knutson (1980) has studied northern dune-building processes on Nauset Spit-Eastham. Dunes 5 meters high and 100 meters wide were built by using snow fencing and planting *Ammophila breviligulata* over a 6-year period. In many cases, dune growth is not limited by the ability of the plant to grow through deep sand burial, but by sand supply or the limited surface area which a plant has to trap windblown sand. *Ammophila arenaria* has repeatedly been reported to grow best in areas of sand accumulation (Marshall, 1965; Tansley, 1968; Ranwell, 1975; Chapman, 1976; Huiskes, 1979).

The accumulation of silt, sand, and organic material in salt marshes has been studied with relation to sea level rise (Ranwell, 1958; Chapman, 1960, 1976; Redfield, 1972). Ranwell (1975) developed a model to describe salt-marsh sedimentation in relation to tidal range, salt-marsh biomass, suspended silt levels, and elevation. Silt accumulation level is negatively correlated to elevation in vegetated areas. Low marsh species experience greater, more consistent levels of sedimentation than higher marsh species. An accumulation of as much as 20 centimeters of silt per year has been recorded in European marshes (Chapman, 1976). Most major salt-marsh grasses are able to keep pace with sediment accumulation by vertical rhizome extension.

The response of grassland vegetation to overwash burial has been studied in North Carolina. Since overwash is common on some of North Carolina's barrier islands, selection pressure has favored plant genotypes adapted to overwash burial. Travis (1976) found that 24 species of flowering plants can recover from overwash burial on the Outer Banks of North Carolina. Godfrey and Godfrey (1974) used artificial burial boxes to demonstrate that *Spartina*

patens is able to recover to initial biomass levels within a year after burial by 30 centimeters of sand. Hosier (1973) reported that burial by 15 centimeters of sand seemed to result in better growth of *Spartina patens* than burial by 5 centimeters. Other studies have shown that *Spartina patens* can recover from as much as 1 meter of sand burial under artificial conditions (Benedict, 1981).

Four dune species, *Ammophila breviligulata*, *Artemisia stelleriana*, *Solidago sempervirens*, *Lathyrus japonicus*, and two salt-marsh species, *Spartina patens* and *Spartina alterniflora*, recovered from overwash burial at the three study sites on Nauset Spit-Eastham in 1977 and 1978. Three dune species, *Agropyron pungens*, *Artemisia caudata*, and *Carex silicea*, which were present in less than three quadrats each, did not recover from overwash burial. *Spartina patens* (var. *monogyna*) recovered from sand burial in two of three uneroded quadrats, but elevation information was not available for analysis. Four salt-marsh species, *Salicornia virginica*, *Limonium nashii*, *Puccinellia* sp., and *Plantago maritima* (Seaside plantain), present in numerous quadrats, did not recover from overwash burial. A review of data available for analysis appears in Table 25. The elevation for each quadrat was surveyed during each field season. Depth of sand burial was calculated from survey data collected in 1977 and 1978. Holes excavated in the washover deposit determined which quadrats were eroded by storms.

Table 25. Quadrat data for analysis of species response to overwash burial.

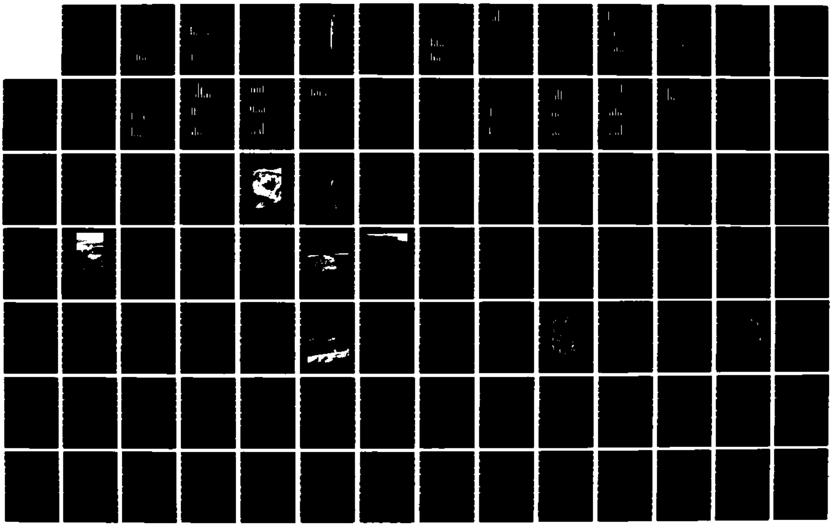
Species	No. of quadrats				Range	Limit
		Eroded	Buried	Recovered		
	1977	1978	1978		(cm)	(cm)
Salt marsh						
Limonium nashii	91	0	91	0	4-88	0
Plantago maritima	37	0	37	0	45-84	0
Puccinellia sp.	180	4	176	0	4-98	0
Salicornia virginica	286	0	286	0	8-98	0
Spartina alterniflora	176	0	176	74	4-116	21
Spartina patens (decumbent)	554	16	538	83	4-116	33
Dune						
Agropyron pungens	21	18	3	0	8-58	0
Ammophila breviligulata	425	317	108	68	5-98[1]	59
Artemisia caudata	10	6	4	0	9-36	0
Artemisia stelleriana	214	137	77	31	5-59	59
Carex silicea	1	0	1	0	51	0
Lathyrus japonicus	88	35	53	24	8-65	43
Solidago sempervirens	56	25	31	12	5-67	56
Spartina patens (upright)	65	62	3	2	---[2]	--

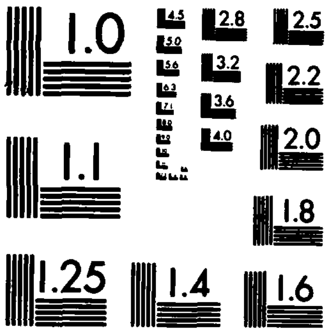
[1] The relief of the steeply scarped edge of the sand road at site 3 was 0.98 centimeter. The next deepest deposit was 0.59 centimeter.

[2] No elevation data were collected at site 1-T in 1977.

AD-A157 433 OVERWASH PROCESSES AND FOREDUNE ECOLOGY NAUSET SPIT MASSACHUSETTS(U) ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MS ENVIR.. R E ZAREMBA ET AL. DEC 84 2/3

UNCLASSIFIED WES/MP/EL-84-8 F/G 6/6 NL




1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

b. <u>Methodology</u>. The 2,567 quadrats sampled at the three research sites on Nauset Spit-Eastham in 1977 were resampled in 1978 after the February 1978 northeaster. Vegetation and elevation data were analyzed using computer programs for simple and multiple linear regression and t-tests (Dixon, 1977). Since most data were not normally distributed about a mean, Kendall's correlation coefficients were calculated for all regression analyses and fed into a program designed to use reduced data (Dixon, 1977). The Kruskal-Wallis test and the Mann-Whitney U-test were used to compare treatment means for nonparametric data, whenever appropriate. An arcsin transformation was used for species cover data, which were expressed as percentages.

c. <u>Analysis of Data</u>.

(1) <u>Dune Species</u>.

(a) <u>*Ammophila breviligulata*</u>. Large sections of the dune at site 3, not eroded during the February storm, were buried by up to 98 centimeters of washover sand. A total of 108 quadrats sampled in 1977 with *Ammophila breviligulata* were buried by between 5 and 98 centimeters of sand; 68 quadrats (63 percent) were recovered from burial (Table 25). Some of the *Ammophila breviligulata* that did not recover may have been eroded during the storm or may have been displaced slightly outside the quadrat.

There is no significant linear relationship between the 1978 (poststorm) cover or density data for *Ammophila breviligulata* and the depth that plants were buried using quadrats containing *Ammophila breviligulata* in 1977 (108 cases) or quadrats that contained recovering *Ammophila breviligulata* in 1978 (68 cases). The data set was divided into the 1977 quadrats with *Ammophila breviligulata* that recovered and those that failed to recover. Using the Kruskal-Wallis test (and the Mann-Whitney U-test) no significant differences were determined for burial depth between the two data sets (Fig. 41). Although 40 quadrats with *Ammophila breviligulata* did not recover from overwash burial, burial depth was probably not a limitation to recovery ability. Plants buried by 60 centimeters of sand recovered as well as plants buried by smaller amounts of sand.

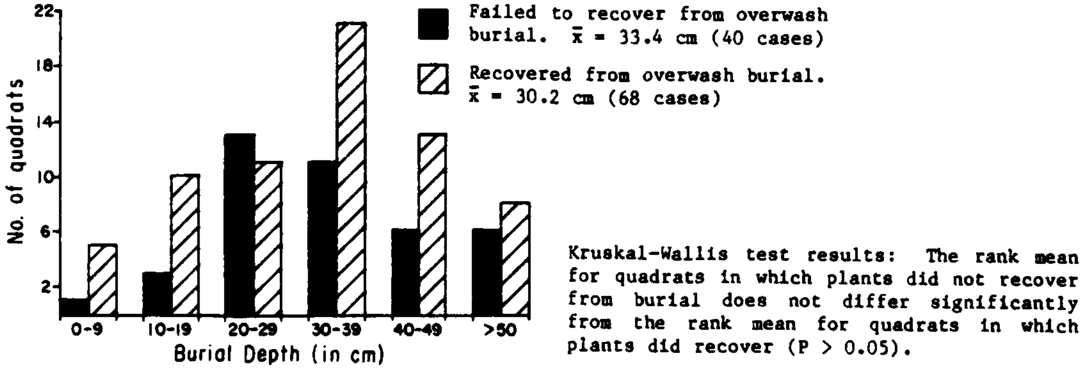
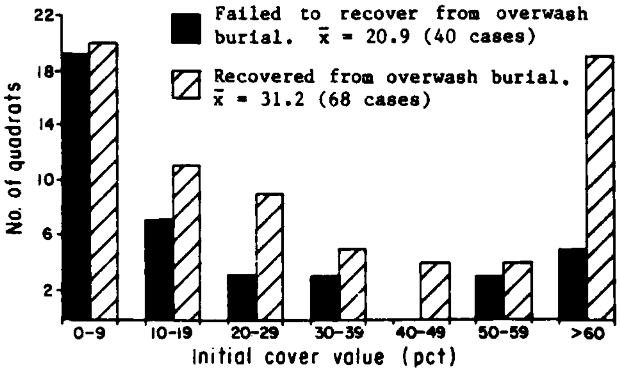


Figure 41. Comparison of burial depths for quadrats of *Ammophila breviligulata* that recovered and failed to recover.

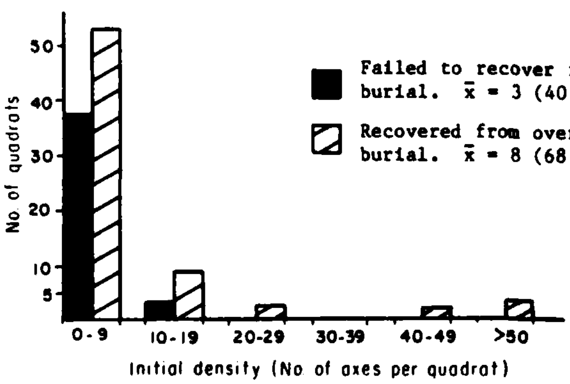
There is a significant linear relationship ($P < 0.05$, $r = 0.245$) between initial (1977) *Ammophila breviligulata* cover and final (postoverwash, 1978) cover for recovering quadrats. The initial cover data mean for quadrats that failed to recover ($\bar{x} = 21$ percent cover) was significantly lower than the initial cover data mean for recovering quadrats ($\bar{x} = 31$ percent cover; Fig. 42). Forty-eight percent of the quadrats (19) that failed to recover had cover values of less than 10 percent; 29 percent of the recovering quadrats (20) had 1977 cover values less than 10 percent. The recovery of quadrats with very low preoverwash *Ammophila breviligulata* was less than quadrats with higher cover values.



Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does differ significantly from the rank mean for quadrats in which plants did recover ($P < 0.05$).

Figure 42. Comparisons of initial cover values for quadrats of *Ammophila breviligulata* that recovered and failed to recover from burial.

There is also a significant linear relationship between initial and final density for recovering quadrats ($P < 0.01$, $r = 0.562$). Initial density for recovering quadrats was highly significantly greater than nonrecovering quadrats (Fig. 43). Eighty percent of the nonrecovering quadrats had fewer than five plants before the storm, while 56 percent of the recovery quadrats initially had fewer than five plants.



Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does differ significantly from the rank mean for quadrats in which plants did recover ($P < 0.01$).

Figure 43. Comparisons of initial density values for quadrats of *Ammophila breviligulata* that recovered and failed to recover from burial.

Multiple-linear regression was used to determine if there were an interaction between initial (1977) cover or density values and burial depth that could lead to a significant prediction of final cover value. A significant relationship was not determined.

Ammophila breviligulata is able to recover from 59 centimeters of overwash sand burial. Plant recovery shows no differential response to burial depth. The physiological limit of *Ammophila breviligulata* for recovering from burial was probably not reached in this field study. Initial cover reflects original aboveground biomass and often may be used to predict final cover. Initial density reflects the number of tillers that can grow through sand deposition. The ability of a plant to grow through a sand deposit must be determined by the amount of stored material (carbohydrates and nitrogenous compounds) that can be remobilized for the large burst of growth needed to reach the new sand surface. Plants that produce high aboveground biomass, measured by the cover figure, are not necessarily those plants with best below-ground biomass and therefore storage capacity. High aboveground biomass may be produced at the expense of stored material, but may also reflect a greater ability to produce photosynthate and therefore greater storage ability. Density data indicate the number of actively dividing apexes present that can grow through sand deposition. While cover and density data for *Ammophila breviligulata* were highly correlated (1977, $r = 0.548$; 1978, $r = 0.522$), density is a much better predictor of recovery ability (cover, $r = 0.245$; density, $r = 0.562$) than cover.

Overwash activity is important in dune-building processes, at least during the early stages of development (Schwartz, 1975). In some areas, overwash swashes will climb low dunes without causing major erosion. Energy will be dissipated and any entrained sediment will settle out on the low dune area, resulting in sand deposition and dune growth. Differential deflation of washovers also leads to the formation of dunes. Hosier (1973) and Godfrey and Godfrey (1974) cite the role of washover sand deposition in the formation of low, *Uniola* dunes in North Carolina. Some overwash deposits contain *Uniola paniculata* (sea oats) fragments that regenerate, grow, and trap sand. The combined action of sand accretion in vegetated areas and unvegetated washover fan deflation led to the formation of small dunes. Dune size is limited by the amount of available sand, which is reduced by (a) the formation of a heavy lag layer of shell and pebble, and (b) the development of dense vegetative cover on the washover fan from recovering or colonizing plants.

Limited areas of the Nauset Spit-Eastham dune line were buried by washover sand. *Ammophila breviligulata* growing on high, well-developed dunes may be either unaffected by overwash or eroded. *Ammophila breviligulata* does not grow in low-lying areas near the ocean or bay beach since it cannot withstand seawater flooding during the growing season. It also does not grow in low-lying areas within the dune field since the freshwater table is very near the sand surface, and *Ammophila breviligulata* roots and rhizomes cannot tolerate waterlogging (Jones and Etherington, 1971). Dunes that are affected by overwash burial and can recover are, therefore, restricted by storm erosion and the natural elevation range of *Ammophila breviligulata*. A transect surveyed in the summer of 1977 and in February, June, and August 1978 is presented with quadrat information in Figure 44. Areas of dense *Ammophila breviligulata* recovered best from overwash burial; areas that did not recover from burial or were unvegetated in 1977 were deflated by the wind. A more generalized model of the overwash role in dune building on northeastern barrier beaches appears in Figure 45.

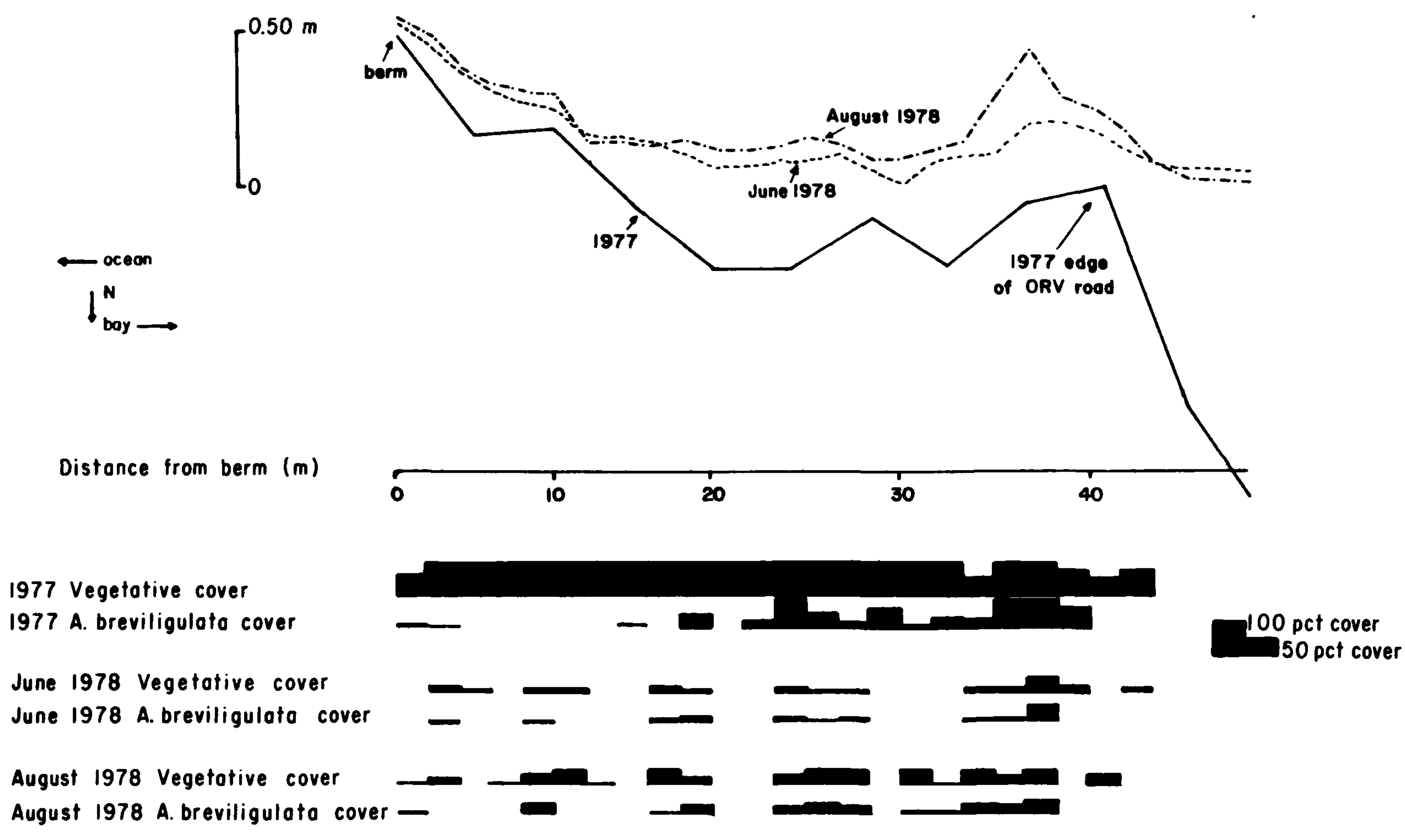


Figure 44. Transect across site 3 throat showing topographic changes in an area with *Ammophila breviligulata* following overwash activity.

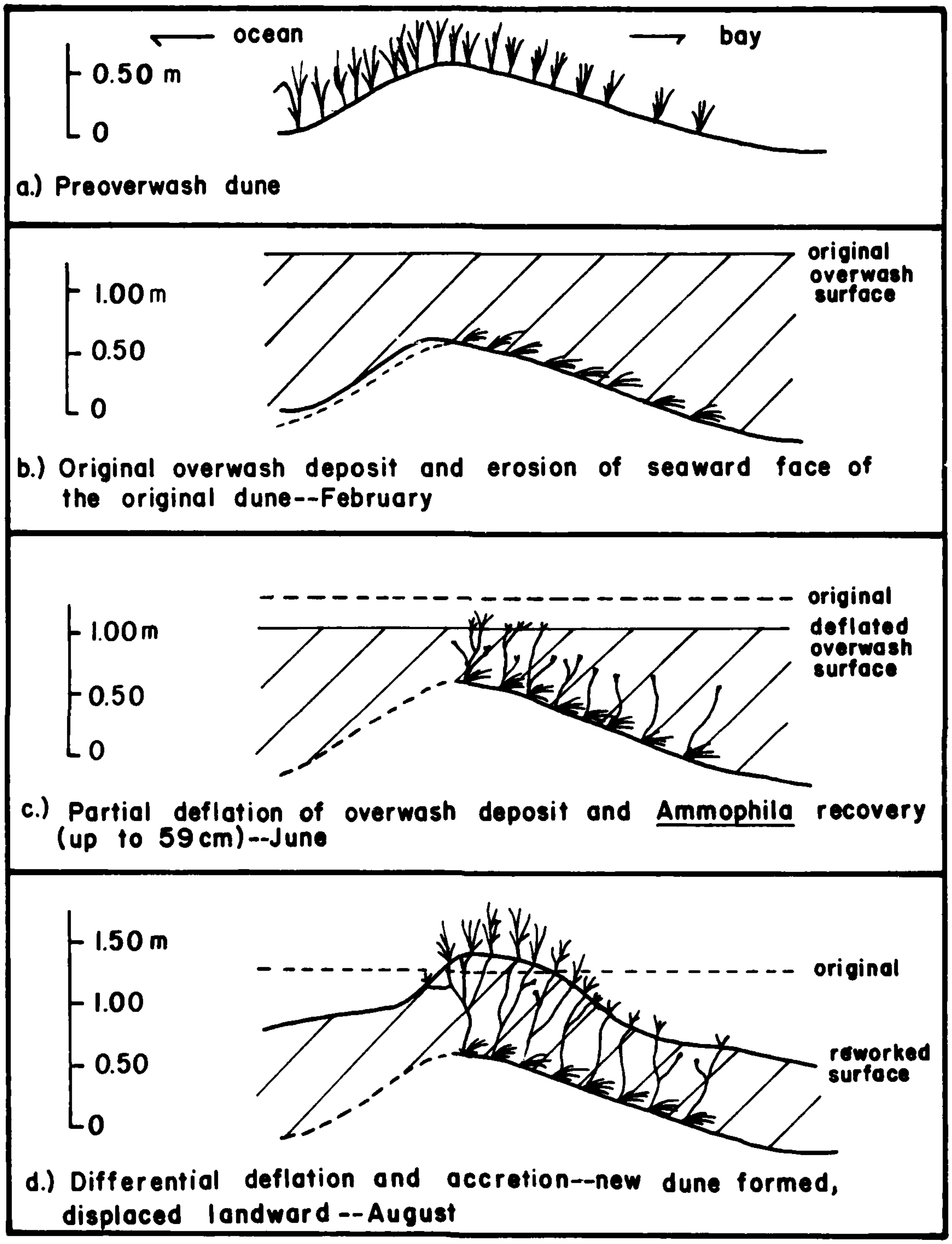


Figure 45. Model of direct overwash involvement in dune building.

Overwash burial of low-lying dunes was limited on Nauset Spit-Eastham in 1978; it was a more common occurrence in areas with very young, accreting dunes, such as the southern end of North Beach in Chatham. Embryonic dunes developing in drift lines and dunes developing as a result of *Ammophila breviligulata* rhizome extension from an established dune field are subject to nonerosive, limited overwash burial. Overwash probably plays a significant role in the early development of vegetated dunes in the northeast by providing large, instantaneous supplies of sand which increase the rate of initial dune development.

(b) *Artemisia stelleriana*. A total of 77 quadrats with *Artemisia stelleriana* were buried by between 5 and 59 centimeters of washover sand. A total of 31 quadrats (40 percent) recovered from as much as 59 centimeters of burial; 46 quadrats failed to recover from burial (Table 25).

Comparisons of quadrats that recovered to those that failed to recover, using the Kruskal-Wallis test, showed that burial recovery is related to initial cover and initial density, but not to burial depth (Figs. 46, 47, and 48). The greatest burial of *Artemisia stelleriana* was 59 centimeters, and the plants in this quadrat recovered. Seventy-five percent of the quadrats (18) with less than 10-percent cover failed to recover from burial. Eighty-eight percent of the quadrats (14) with fewer than 10 plants per 50 square centimeters failed to recover. There is no correlation between either initial and final cover or initial and final density. Multiple linear regression was used to relate burial depth and initial cover to final cover. Final cover can be predicted using initial cover and burial depth ($r = 0.493$, $P < 0.02$).

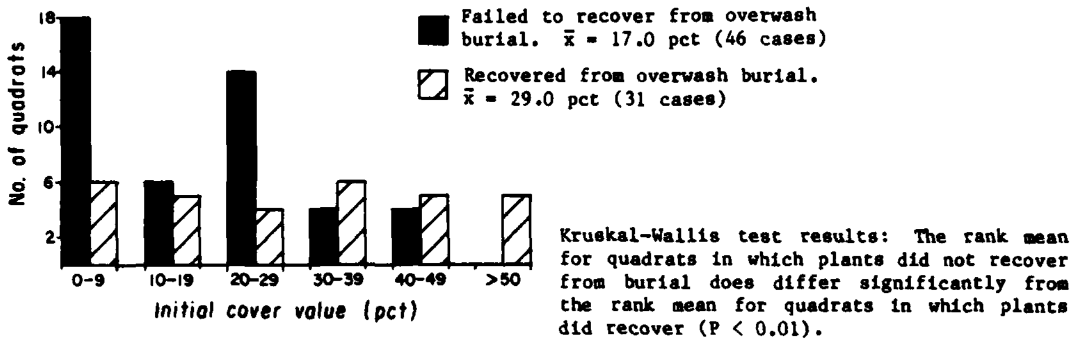


Figure 46. Comparisons of initial cover values for quadrats of *Artemisia stelleriana* that recovered and failed to recover from burial.

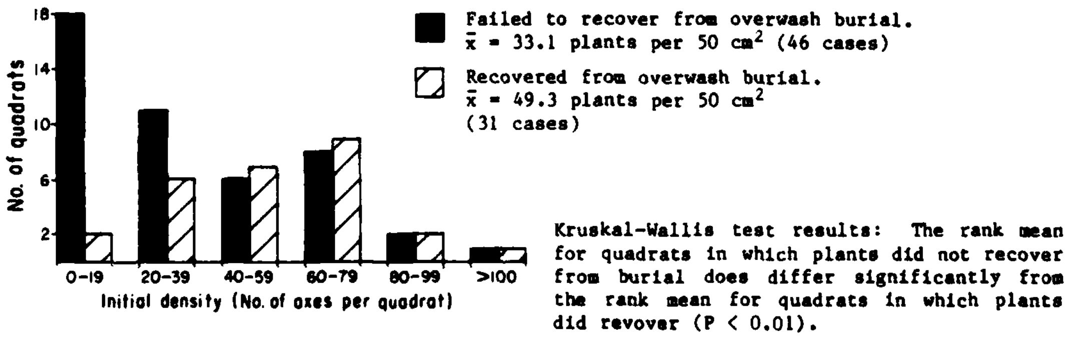
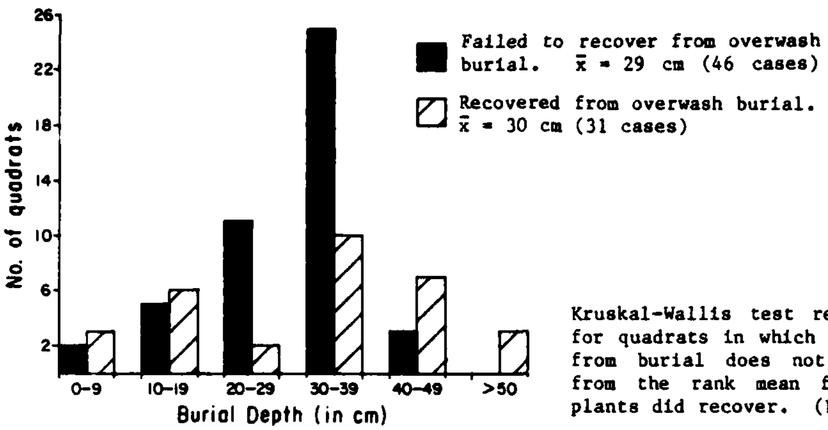


Figure 47. Comparisons of initial density for quadrats of *Artemisia stelleriana* that recovered and failed to recover from burial.



Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does not differ significantly from the rank mean for quadrats in which plants did recover. ($P > 0.05$).

Figure 48. Comparisons of burial depth for quadrats of *Artemisia stelleriana* that recovered and failed to recover.

Artemisia stelleriana is able to recover from 59 centimeters of overwash burial. Recovery is not dependent on burial depth, but is dependent on initial cover and density. The limit of *Artemisia stelleriana* to grow through sand was probably not reached in this field study. Multiple regression showed that there is a significant linear relationship between depth and initial cover and final cover. This relationship reflects the fact that plants recovering from deep burial do not produce as high a total aboveground biomass the first year after burial as plants that are buried by less sand. The relationship of cover data to density data can be used as a measure of individual plant size. The slope of the regression line, describing the linear relationship between cover and density, was greater in 1978 (11.78) than it was in 1977 (0.422), suggesting that fewer plants in 1978 contributed to any given cover level. Individual axes of *Artemisia stelleriana* were larger in 1978 than in 1977, although the actual number of axes was much lower in 1978 than in 1977. Burial in some way stimulates *Artemisia stelleriana* growth. Fewer axes have a larger resource base to utilize and may expend less energy in both intraspecific and interspecific competition for light, moisture, and nutrients. Under typical drift line or dune conditions, *Artemisia stelleriana* plants may be buried by a few centimeters of sand each year. Buried axillary buds break and new aboveground axes are formed creating a circular mass. In areas that receive little aeolian sand, *Artemisia stelleriana* plants are made up of small scattered axes. *Artemisia stelleriana* grows best in recent drift lines or on low dunes, which experience low-level burial and receive maximum solar radiation; it is almost never found on well-established building dunes. *Ammophila breviligulata* grows best in accreting areas and may fatally shade out the low-growing *Artemisia stelleriana* plants. Seedlings of *Artemisia stelleriana* have been found only in drift lines during the past three field seasons. Individual plants found in dunes probably originate from either seedlings in drift lines or from fragment regeneration. *Artemisia stelleriana* can recover from continuous, low-level burial and appears to recover from high levels of burial, but would probably fail to keep pace with continuous high-level burial (either from overwash or aeolian processes). Overall plant density and cover are significantly reduced by overwash.

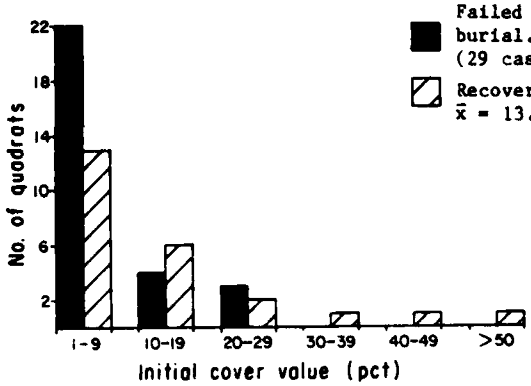
(c) *Lathyrus japonicus*. Fifty-three quadrats with *Lathyrus japonicus* were buried by between 8 and 65 centimeters of washover sand. A total of 24 quadrats (44 percent) recovered from as much as 43 centimeters of burial; 29 quadrats failed to recover from overwash burial.

Comparisons of recovered quadrats to quadrats that failed to recover, using the Kruskal-Wallis test, showed that burial recovery is related to initial cover but not related to initial density or burial depth (Figs. 49, 50, and 51). Using the 24 recovered quadrats, it was found that plant recovery is not linearly related to burial depth, initial cover, or initial density. Correlations were not found among any of the variables using multiple regression. In 1977 there was no relationship between density and cover for *Lathyrus japonicus*; but in 1978 there was a highly significant relationship between density and cover ($r = 0.589$, $P < 0.01$).

Lathyrus japonicus can recover from as much as 43 centimeters of overwash burial. Brightmore and White (1963) reported that *Lathyrus japonicus* can grow through as much as 40 centimeters of aeolian sand burial. Plant recovery shows no differential response to burial depth. Plants buried by 43 centimeters recover to biomass levels comparable to plants buried by less sand. The physiological limit of *Lathyrus japonicus* may not have been reached in the data available for analysis. The growth form of *Lathyrus japonicus* and the sampling technique used may explain the correlation between initial and final density. Well-established *Lathyrus japonicus* plants are larger than other dune plants. A single aboveground axis commonly measures more than 40 centimeters. Density figures were calculated for all plants in both dune and marsh areas using the number of individual axes breaking the substrate surface within the 50-square-centimeter quadrat. Density and cover data for 1977 were not correlated for *Lathyrus japonicus* because many individuals may have been present in a quadrat but anchored in an adjacent area. Lateral buds break dormancy along the *Lathyrus japonicus* stem just as in other dune and salt-marsh plants, but internode length is much longer than in the other plants that were analyzed. The amount of rhizome or stem and the number of individual leaves present in any given quadrat will determine the number of axillary buds (plus the original apex) present. A plant may be anchored in a quadrat but have no apical meristem or lateral bud present.

Unlike 1977, the 1978 cover and density for *Lathyrus japonicus* were highly correlated. Recovering plants broke the sand surface in early June, which was later than other recovering plants in the area. Individual plant growth was robust during the summer, but aboveground internode length was much shorter than in plants not affected by overwash burial or deep aeolian deposits. Plants were more densely oriented about the central axis in 1978.

Lathyrus japonicus grows on well-established, accreting dunes although *Ammophila breviligulata* growth may be very dense. *Lathyrus japonicus*, as all dune species, requires high light intensity but is able to compete with *Ammophila breviligulata* for light by internode elongation. *Lathyrus japonicus* plants found in high dunes with *Ammophila breviligulata* have extremely long axes with long internodes. As with *Artemisia stelleriana*, no seedlings of *Lathyrus japonicus* were found in established high dunes. *Lathyrus japonicus* frequently seeds in drift lines and can regenerate from rhizome fragments. Plants found on high dunes were probably originally established in very low areas and grew through washover and aeolian sand deposits. New dunes can be colonized by the massive lateral rhizome systems of *Lathyrus japonicus* plants.

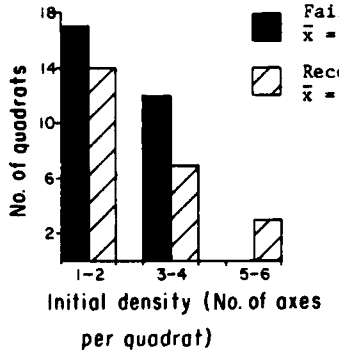


Failed to recover from overwash burial. $\bar{x}$ = 5.76 pct cover (29 cases)

Recovered from overwash burial. $\bar{x}$ = 13.4 pct cover (24 cases)

Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does differ significantly from the rank mean for quadrats in which plants did recover ($P < 0.01$).

Figure 49. Comparisons of initial cover values for quadrats of *Lathyrus japonicus* that recovered and failed to recover from burial.

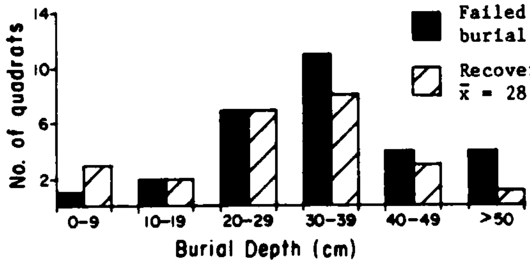


Failed to recover from overwash burial. $\bar{x}$ = 1.66 plants per 1/4 m^2 (29 cases)

Recovered from overwash burial. $\bar{x}$ = 1.79 plants per 1/4 m^2 (24 cases)

Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does not differ significantly from the rank mean for quadrats in which plants did recover ($P > 0.05$).

Figure 50. Comparisons of initial density values for quadrats of *Lathyrus japonicus* that recovered and failed to recover from burial.



Failed to recover from overwash burial. $\bar{x}$ = 33 cm (29 cases)

Recovered from overwash burial. $\bar{x}$ = 28 cm (24 cases)

Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does not differ significantly from the rank mean for quadrats in which plants did recover ($P > 0.05$).

Figure 51. Comparisons of burial depths for quadrats of *Lathyrus japonicus* that recovered and failed to recover.

(d) *Solidago sempervirens*. Thirty-one quadrats with *Solidago sempervirens* were buried by between 5 and 67 centimeters of washover sand. *Solidago sempervirens* in 12 quadrats (38 percent) recovered from as much as 56 centimeters of burial; a total of 19 quadrats failed to recover from overwash burial (Table 25).

Comparisons of recovered quadrats to quadrats that failed to recover, using the Kruskal-Wallis test, show that recovery from burial is not related to initial cover, initial density, or burial depth (Figs. 52, 53, and 54).

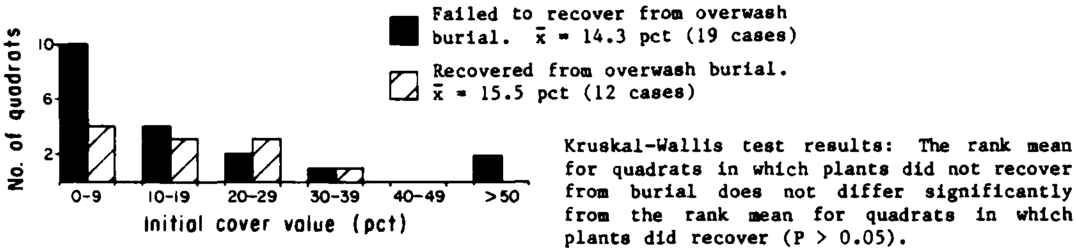


Figure 52. Comparisons of initial cover values for quadrats of *Solidago sempervirens* that recovered and failed to recover from burial.

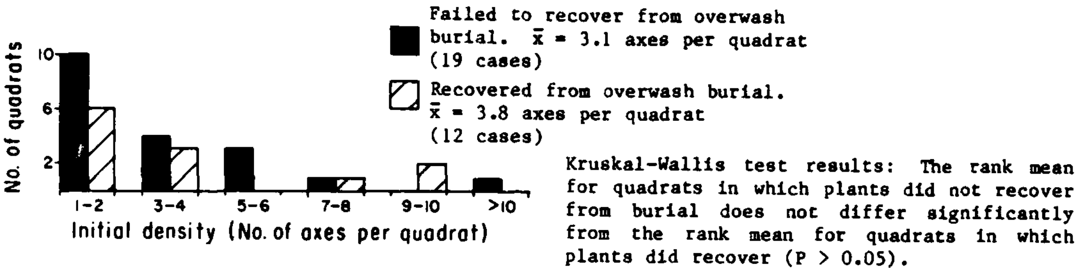


Figure 53. Comparisons of initial density values for quadrats of *Solidago sempervirens* that recovered and failed to recover from burial.

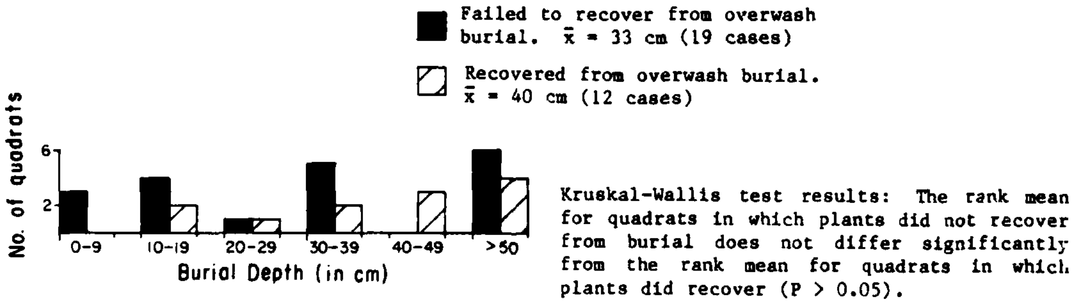


Figure 54. Comparisons of burial depths for quadrats of *Solidago sempervirens* that recovered and failed to recover.

Using the 12 quadrats that recovered from burial, it was found that plant recovery is not correlated to initial cover, initial density, or depth of burial using multiple regression. In both 1977 and 1978, correlation between cover and density for *Solidago sempervirens* was highly significant (1977, $P < 0.01$, $r = 0.421$; 1978, $P < 0.01$, $r = 0.878$).

Solidago sempervirens can recover from as much as 56 centimeters of overwash burial. Plant recovery showed no differential response to varying burial depth. The physiological limit of *Solidago sempervirens* to grow through sand deposits may not have been reached using the available data, but four quadrats with more than 56 centimeters of overwash burial did fail to recover. Quadrats with high cover and density did not recover from burial any better than quadrats with low cover and density. *Solidago sempervirens* plants can vary

in size. Individual plants sampled in site 3 ranged in size from 1- to 24-percent cover in a 50-square-centimeter quadrat. *Solidago sempervirens* has the largest below-ground storage organs of the species studied. Roots form adventitiously along buried stems which can reach more than 1 centimeter in diameter.

In both 1977 and 1978, cover data were highly correlated to density data. The slope of the regression line can be used as a measure of plant size. The slope in 1978 (11.06) greatly exceeded the slope in 1977 (1.95). The number of individual *Solidago sempervirens* axes in the noneroded quadrats in site 3 was significantly reduced by overwash burial (1977, 102 axes; 1978, 36 axes). Plant cover for *Solidago sempervirens* was, however, not significantly reduced (1977, 2.77 percent; 1978, 2.34 percent; $P > 0.05$). One-third of the plants were covering a statistically similar amount of surface area. Overwash burial reduces the number of individual axes (plants) but stimulates plant growth. *Solidago sempervirens* plants affected by overwash are approximately three times larger than unaffected plants.

Like *Lathyrus japonicus*, *Solidago sempervirens* grows well on accreting dunes, although high *Ammophila breviligulata* biomass may reduce *Solidago sempervirens* cover substantially. *Solidago sempervirens* seedlings have been found on high dunes. Seedlings and regenerating fragments of *Solidago sempervirens* are also found in drift lines.

(e) Discussion. The four dune species that made up 95.3 percent of the I.V. of site 3 in 1977 were all able to recover from overwash burial. In all cases, these species were able to recover from instantaneous burial during the dormant season that equaled or exceeded typical annual aeolian burial levels. Of the four species, *Ammophila breviligulata* recovers most effectively (63 percent) from overwash burial. None of the dune species showed a differential response to burial depth. A review of the effect of overwash on the site 3 community that was not eroded away appears in Table 26. The I.V. of *Ammophila breviligulata*, *Lathyrus japonicus*, and *Solidago sempervirens* increased; the I.V. of *Artemisia stelleriana* decreased. Although the recovering percentage for *Solidago sempervirens* (38 percent) was lower than for *Artemisia stelleriana* (40 percent), the percent cover for *Solidago sempervirens* was statistically similar in 1977 and 1978, while *Artemisia stelleriana* declined significantly (Table 26).

Table 26. The effect of overwash on the importance value of species in noneroded areas of site 3 (137 quadrats), 1978.

Species	Quadrats with plants that recovered (pct)	I.V.	Change (pct)	I.V.
Ammophila breviligulata	63	108.8	+24	134.5
Artemisia stelleriana	40	130.3	-30	91.8
Lathyrus japonicus	44	27.6	+47	40.6
Solidago sempervirens	38	19.3	+55	29.78

Rapidly accreting dunes are dominated by *Ammophila breviligulata*, with *Lathyrus japonicus* and *Solidago sempervirens* as subdominants. *Artemisia stelleriana* was the dominant species (I.V. = 130.3) in site 3 before overwash. This area had been stable, receiving little wind-transported sand. *Ammophila breviligulata* is frequently reported to grow poorly in stable dune areas such as site 3 in 1977 (Ranwell, 1964). Overwash in 1978 increased *Ammophila breviligulata* cover and density in relation to other species and revived dune building. *Artemisia stelleriana* is likely to decline in importance as dunes continue to develop.

The data available for analysis in the dune community on Nauset Spit-Eastham are representative of the range of possible dune areas affected by overwash activity. Dune communities on a barrier beach are restricted to areas above certain minimum elevations. On the ocean and bay side of the barrier beach, dune vegetation is limited to those areas not inundated by tides during the growing season. In the interior of the dune field, *Ammophila breviligulata*, the principal dune species, is restricted to areas that are not water-logged due to water-table conditions. There is not a maximum elevation at which *Ammophila breviligulata* will grow; it is found on sand dunes of more than 50 meters. Other dune species are limited by their ability to grow through continuous sand burial, or less frequently, through large amounts of sand burial from overwash activity. Biomass levels in dune areas are not correlated with elevation. *Ammophila breviligulata*, which grows poorly on dunes that are partially inundated by tides or at low elevations, does not necessarily grow better on the highest dunes. *Ammophila breviligulata* grows best on seaward dune slopes (van der Valk, 1974) and in areas that receive continuous sand burial (Ranwell, 1975). *Ammophila breviligulata* rapidly loses vigor on high dunes that are not accreting.

Although only a limited number of supratidal quadrats (137) in site 3 throat were not eroded by the February 1978 northeaster, this area does represent typical dunes affected by overwash processes. The four major dune species on Nauset Spit-Eastham were present in sufficient numbers for analysis.

(2) Salt-Marsh Species. Site 1 was the only sampled area that had low-level overwash burial and plant recovery in the salt marsh. Sand deposition ranged from 6 to 118 centimeters. *Spartina patens* and *Spartina alterniflora* in 134 quadrats recovered from 6 to 33 centimeters of burial. Data from site 2 and site 3 yielded little information concerning the vegetative response to overwash activity; it was shown, however, that salt-marsh plants do not recover from 33 centimeters or more of overwash burial (site 3) or from continuous overwash during the growing season (site 2).

Salt-marsh species distribution is highly correlated to elevation. Salt-marsh plants do not grow below MSL and do not grow above spring high water (Redfield, 1972), with the exception of *Spartina patens* (var. *monogyna*) which grows on low-lying dunes. Unlike dune species, biomass levels for individual salt-marsh species are highly correlated to elevation. *Spartina alterniflora* grows best at the lowest elevations within its range. A band of *Spartina patens* occurs at the high elevations in the salt marsh, but *Spartina patens* grows best at the lower elevations within its range, when not coexisting with *Spartina alterniflora*. Density data for both species are highly correlated with elevation.

Overwash sand deposition can occur at all elevations in a salt marsh. The depth of sand deposition was highly correlated with elevation at sites 1 and 3 during 1978. A series of high-velocity overwash surges deposit sand toward the fan terminus. Final surges of low velocity exhibit less penetration, and deposition occurs closer to the barrier threshold (washover throat).

The poststorm washover feature is a series of microterraces, composed of steeply sloping foreset beds at the fan terminus. Reworking by tidal currents subsequently redistributes the sand around the perimeter of the fan, destroying the terraced features. At Nauset Spit-Eastham, the greatest deposition occurred on the road to the lee of the dune line.

If a washover were to extend across the entire marsh to the bay, creating a gently sloping planar feature, there would be a negative correlation between burial depth and elevation. The greatest deposition would occur at low elevations. Deposition levels could be predicted from the slope and elevation of the washover feature.

Burial depth is a factor of storm conditions. Overwash surges that reach the marsh or bay deposit greatest amounts of sand in low-lying areas; smaller surges that dissipate their energy across the fan surface deposit most of their sand at higher elevations (Fig. 55). Prior to the February 1978 storm, sand deposition on all washovers on Nauset Spit-Eastham had been positively correlated with elevation (case I). Since the February 1978 storm, sand deposition on most washovers is negatively correlated with elevation (case II).

Salt-marsh plant recovery from overwash is related to burial depth and elevation. The data available for analysis from site 1 fan, an area representative of washover case I, present a limited number of the possible vegetative relationships between depth of burial, elevation, and recovery on a barrier beach. The entire elevation range of *Spartina patens* and *Spartina alterniflora* is not present in the data. There is a good representation of the elevation range in which both *Spartina patens* and *Spartina alterniflora* occur together. The upper elevation limit where *Spartina alterniflora* grows poorest is well represented. Neither the lower limit of the range of *Spartina patens* nor the lower limit of the range of *Spartina alterniflora* is present under conditions that allow plant recovery (i.e., burial exceeds limits of the species).

While 134 quadrats in site 1 recovered from burial, this area represents only some of the possible situations on a northeast barrier beach. Other washovers on Nauset Spit-Eastham resemble site 1 fan (case I, Fig. 55), but the majority of the washovers are broad, flat areas extending either far into the low marsh zone or into the bay itself (case II).

(a) *Spartina patens*. The 538 quadrats sampled in 1977 that contained *Spartina patens* were buried by between 4 and 116 centimeters of washover sand (Table 25). A total of 83 quadrats (15 percent) recovered from as much as 33 centimeters of burial; 455 quadrats failed to recover from overwash burial. All quadrats with *Spartina patens* in site 3 were buried by more than 34 centimeters of sand; all quadrats in site 2, which continued to overwash until July, did not recover. Using only those quadrats in site 1 that were buried by less than 34 centimeters of sand (166 cases), 50 percent of the quadrats (83 cases) with *Spartina patens* recovered.

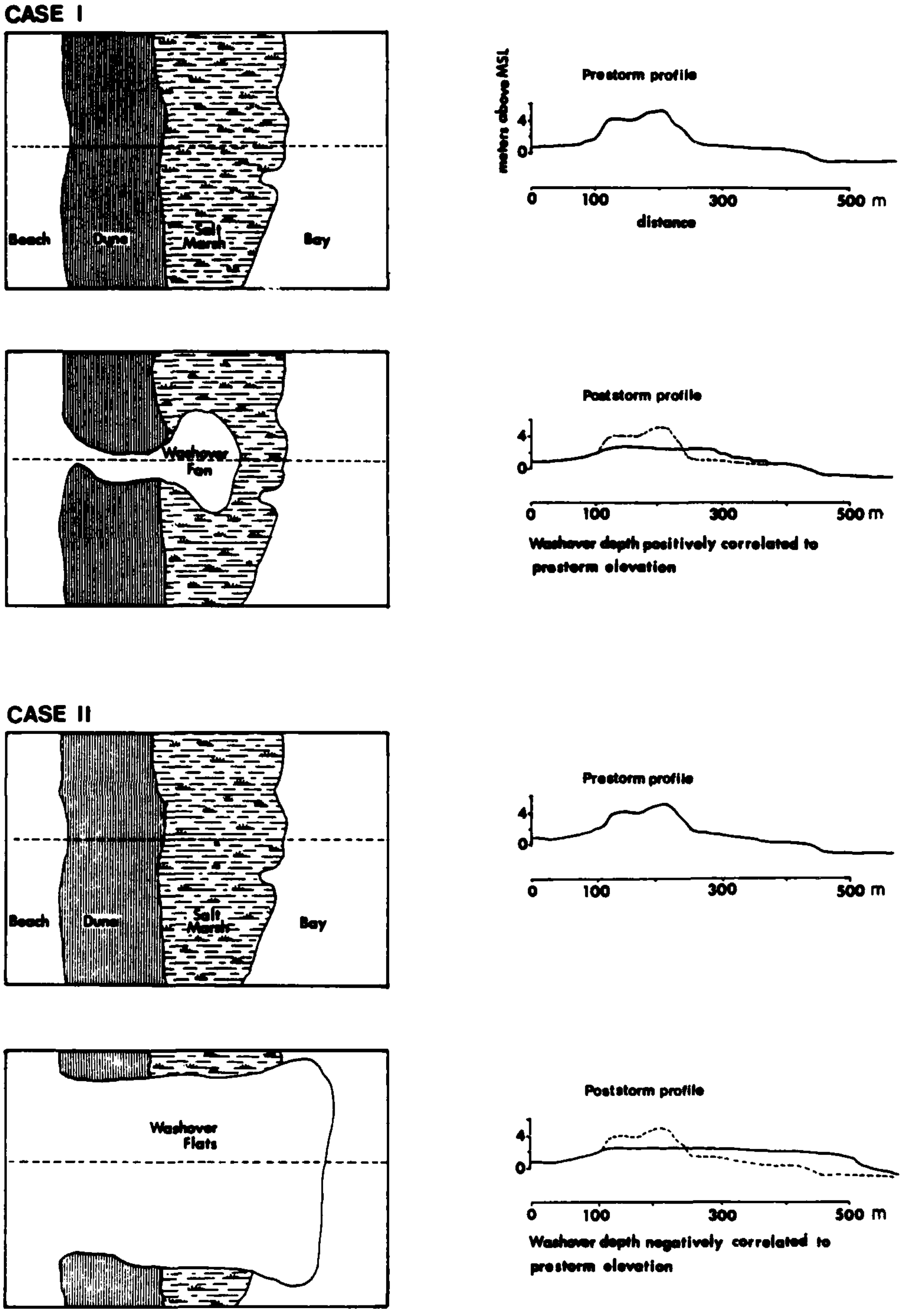
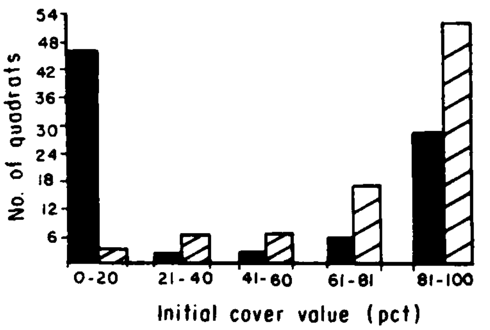


Figure 55. Two cases of washover burial: (I) washover fan and (II) washover flats.

Comparisons of recovered quadrats to quadrats that failed to recover (using site 1 quadrats that were buried by less than 34 centimeters of sand) showed that burial recovery for *Spartina patens* is related to burial depth, initial (preoverwash) elevation, final (postoverwash) elevation, initial cover and density of *Spartina patens*, and initial and final cover and density of *Spartina alterniflora* present in the same quadrats (Figs. 56 to 64). Using all quadrats with *Spartina patens* that received less than 34 centimeters of burial, it was found that there was a negative linear correlation between burial recovery (measured by 1978 cover or density for *Spartina patens*) and burial depth (density, $P < 0.05$, $r = 0.180$; cover, $P < 0.01$, $r = 0.217$). Initial cover (1977), however, is not linearly related to final cover (1978), nor is there a correlation between initial and final density. In 1977 the magnitude of *Spartina patens* cover and density was highly correlated with elevation, but in 1978 no such correlation was found. General elevation data for quadrats containing *Spartina patens* in 1977 and 1978 appear in Figure 65. For both 1977 and 1978, cover and density data for *Spartina patens* were highly correlated (1977, $r = 0.868$, $P < 0.01$; 1978, $r = 0.882$, $P < 0.01$). A comparison of the two regression lines using a t-test showed that the slopes are significantly different ($P < 0.01$). Multiple regression was used in an attempt to develop a model for *Spartina patens* recovery based on data collected in 1977 and 1978. Recovery is related linearly only to burial depth when data for quadrats receiving less than 34 centimeters of sand are considered. Elevation (both initial and final), initial cover, and density of *Spartina alterniflora* do not improve a predictive model for *Spartina patens* recovery from overwash burial.

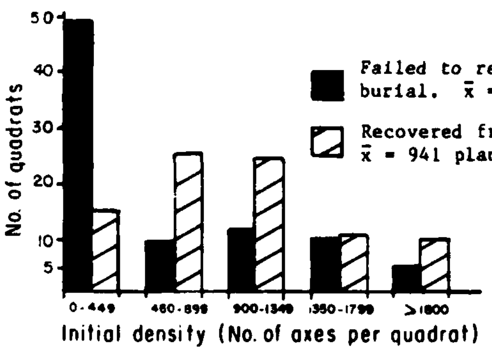


Failed to recover from overwash burial. $\bar{x}$ = 40.4 pct (83 cases)

Recovered from overwash burial. $\bar{x}$ = 80.5 pct (83 cases)

Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does differ significantly from the rank mean for quadrats in which plants did recover ($P < 0.01$).

Figure 56. Comparisons of initial cover values for quadrats of *Spartina patens* that recovered and failed to recover from overwash burial.



Failed to recover from overwash burial. $\bar{x}$ = 525 plants (83 cases)

Recovered from overwash burial. $\bar{x}$ = 941 plants (83 cases)

Kruskal-Wallis test results: The rank mean for quadrats in which plants did not recover from burial does differ significantly from the rank mean for quadrats in which plants did recover ($P < 0.01$).

Figure 57. Comparisons of initial density values for quadrats of *Spartina patens* that recovered and failed to recover from overwash burial.

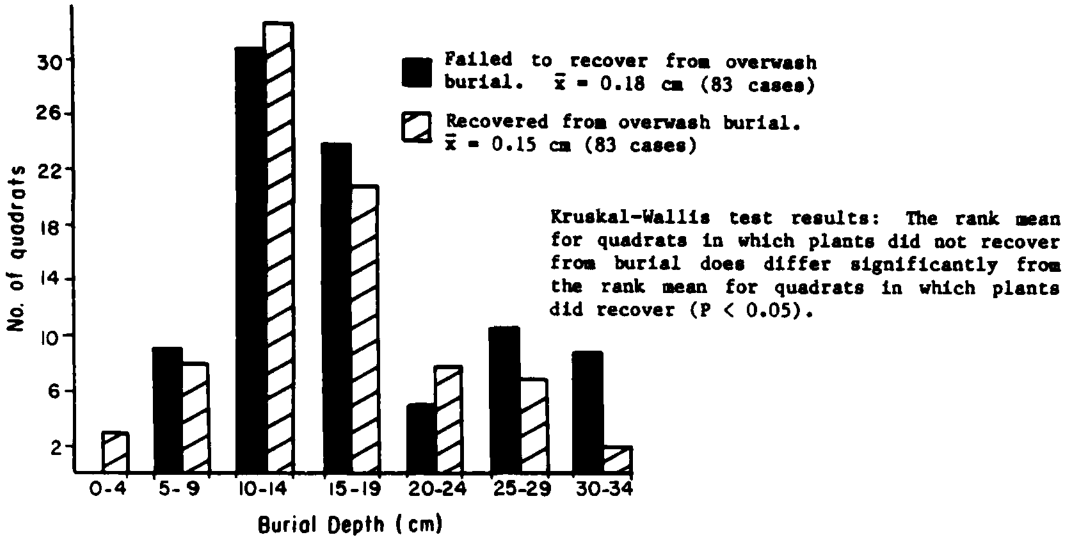


Figure 58. Comparisons of burial depths for quadrats of *Spartina patens* that recovered and failed to recover.

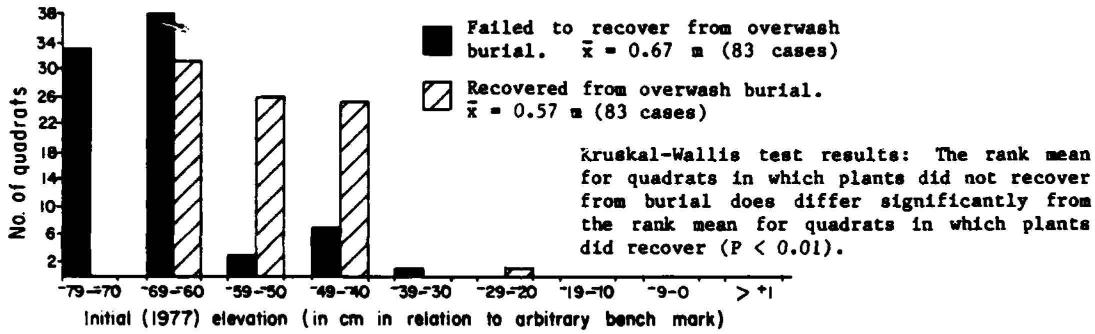


Figure 59. Comparisons of prestorm elevations for quadrats of *Spartina patens* that recovered and failed to recover from burial.

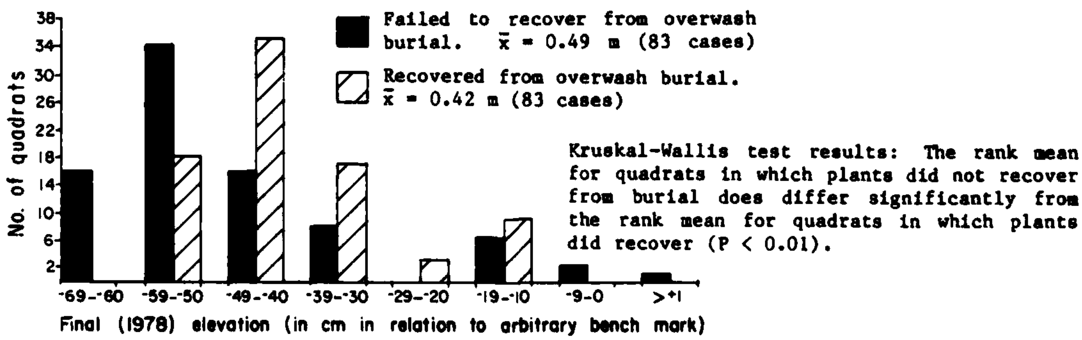


Figure 60. Comparisons of poststorm elevations for quadrats of *Spartina patens* that recovered and failed to recover from burial.

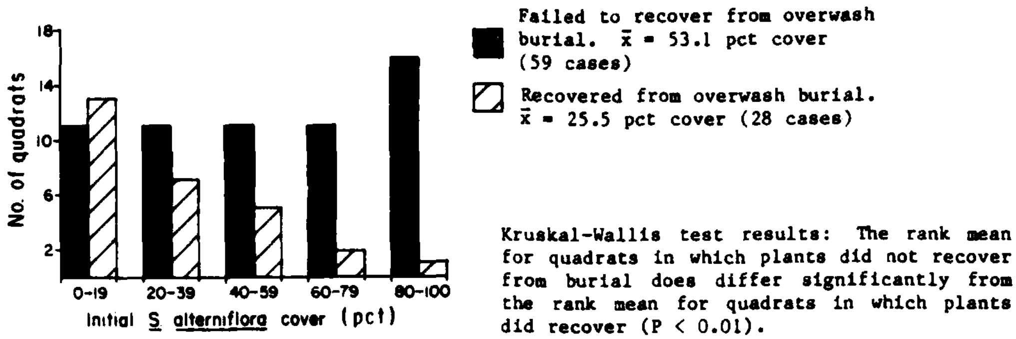


Figure 61. Comparisons of preoverwash cover for quadrats of *Spartina alterniflora* that also contained *Spartina patens* which recovered and failed to recover from burial.

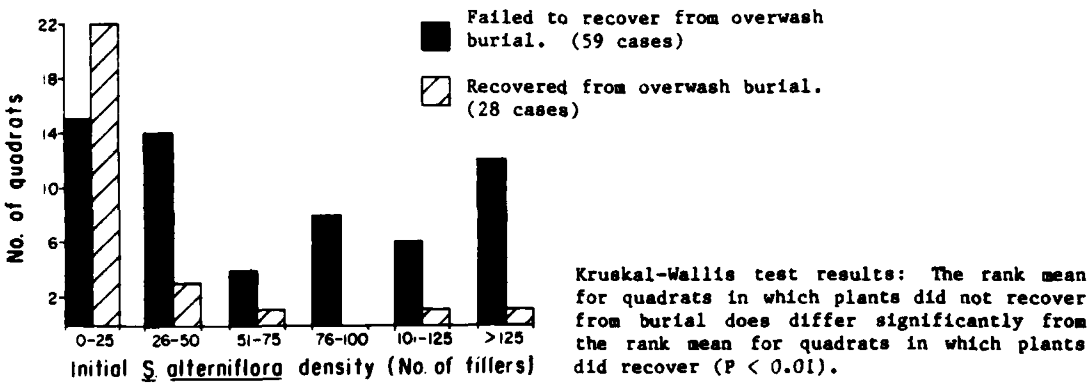


Figure 62. Comparisons of preoverwash density for quadrats of *Spartina alterniflora* that also contained *Spartina patens* which recovered and failed to recover from burial.

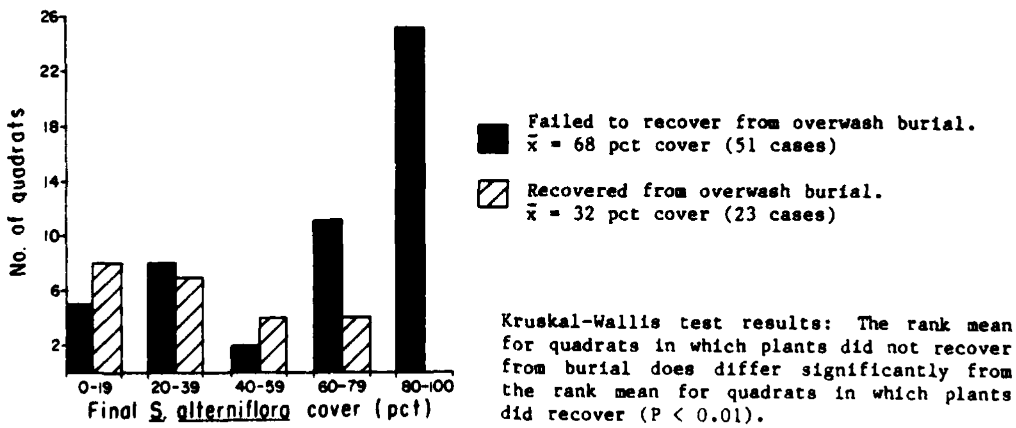


Figure 63. Comparisons of postoverwash cover for quadrats of *Spartina alterniflora* that also contained *Spartina patens* which recovered and failed to recover from burial.

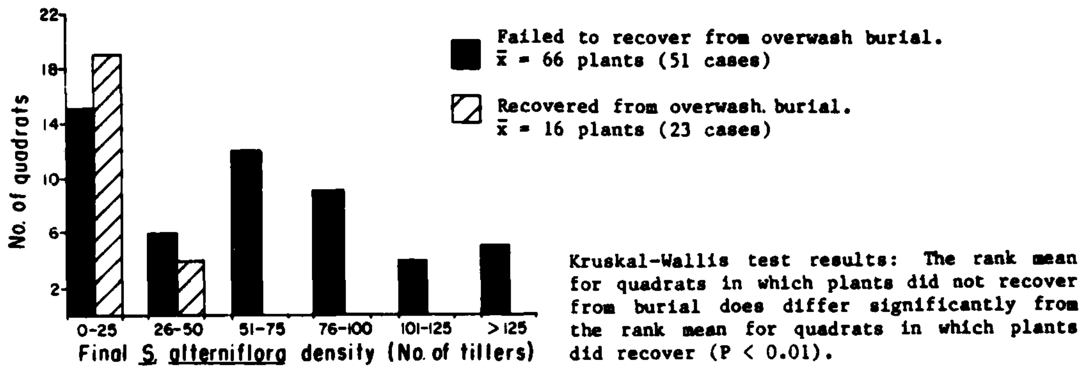


Figure 64. Comparisons of postoverwash density for quadrats of *Spartina alterniflora* that also contained *Spartina patens* which recovered and failed to recover from burial.

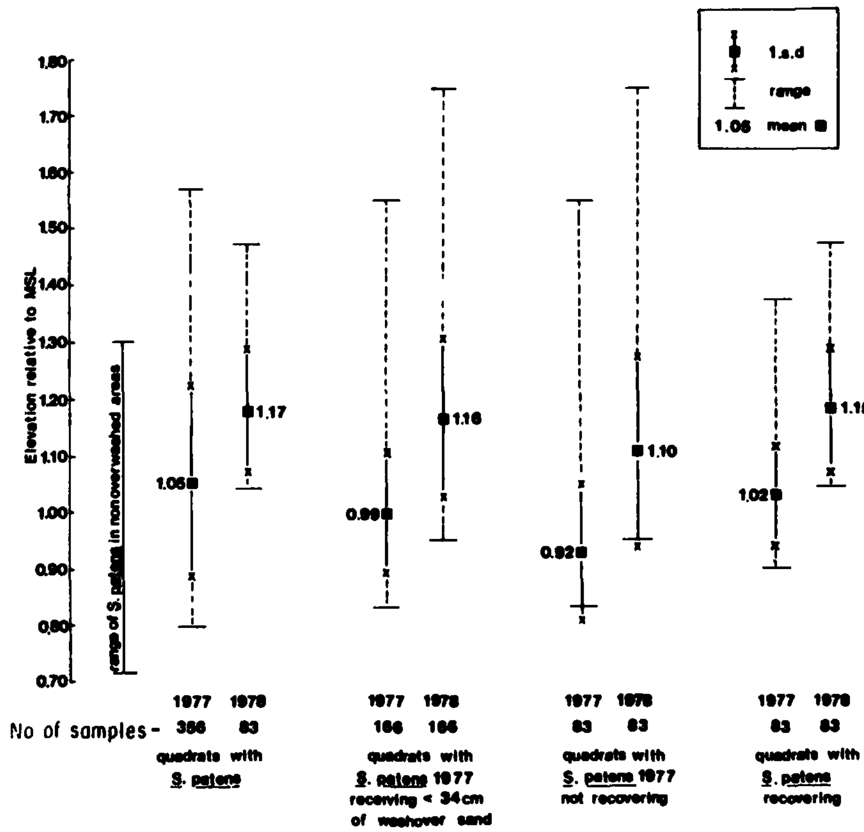


Figure 65. Elevations for quadrats with *Spartina patens* at site 1 fan, 1977 to 1980.

Spartina patens is able to recover from 33 centimeters of overwash sand burial. Unlike the dune species, plant recovery for *Spartina patens* is negatively correlated to burial depth; *Spartina patens* recovers best from shallow burial. Although there is no linear relationship between elevation and recovery, quadrats at higher elevations recovered better than those at lower elevations. The elevation range over which *Spartina patens* occurred decreased from 77 centimeters in 1977 to 43 centimeters in 1978. The mean elevation at which *Spartina patens* occurred increased by 12 centimeters. Preoverwash density and cover of *Spartina patens* cannot be used to predict postoverwash density and cover, but quadrats with high density and cover did recover better than those with lower density and cover.

In 1977 both cover and density of *Spartina patens* were highly negatively correlated with elevation. *Spartina patens* grew best at the lower limits of its elevation range. In 1978, however, there was no relationship between cover and density and elevation. Plants that were able to grow through sand burial did equally well throughout the 43-centimeter elevation range. Only after initial colonization of the sand surface does the species respond to subtle variations in environmental conditions based on elevation.

Cover and density were highly correlated in both 1977 and 1978. Regression lines for 1977 and 1978 were highly significantly different. The relationship of density to cover, used as a measure of individual plant size, indicated that plants were larger after recovering from overwash burial than before burial. All the preoverwash vegetative axes did not recover from burial. Plant density was reduced significantly, even in those quadrats that recovered from burial. Those axes that reached the sand surface were probably able to use a larger amount of the reallocatable resources of the buried plant parts than axes unaffected by overwash burial. *Spartina patens* generally grows poorly in areas that had high biomass the previous year. Unlike *Spartina alterniflora*, much of the dead *Spartina patens* plant material remains in place for several years, shading newly emergent axes and reducing biomass production. In overwashed areas, dead plant material is buried such that emergent axes receive maximum solar radiation and grow better than plants with limited light.

Spartina patens recovers best in quadrats that in 1977 had fewest *Spartina alterniflora*; these quadrats were in the lower range of *Spartina patens*. The negative association of *Spartina patens* and *Spartina alterniflora* may reflect the inability of *Spartina patens* to recover from burial at low elevations as much as *Spartina patens*' ability to recover from burial in the presence of *Spartina alterniflora*. A model for *Spartina patens* recovery in site 1 fan appears in Figure 66.

(b) *Spartina alterniflora*. The 176 quadrats sampled at site 1 fan in 1977 with *Spartina alterniflora* were buried by between 4 and 116 centimeters of washover sediment (Table 25). A total of 74 quadrats (42 percent) recovered from as much as 22 centimeters of burial; 102 quadrats failed to recover from burial. All quadrats with *Spartina alterniflora* in sites 2 and 3 were buried by more than 22 centimeters of overwash sand. Using only those quadrats in site 1 that were buried by less than 22 centimeters of sand (133 cases), 56 percent of the quadrats with *Spartina alterniflora* recovered.

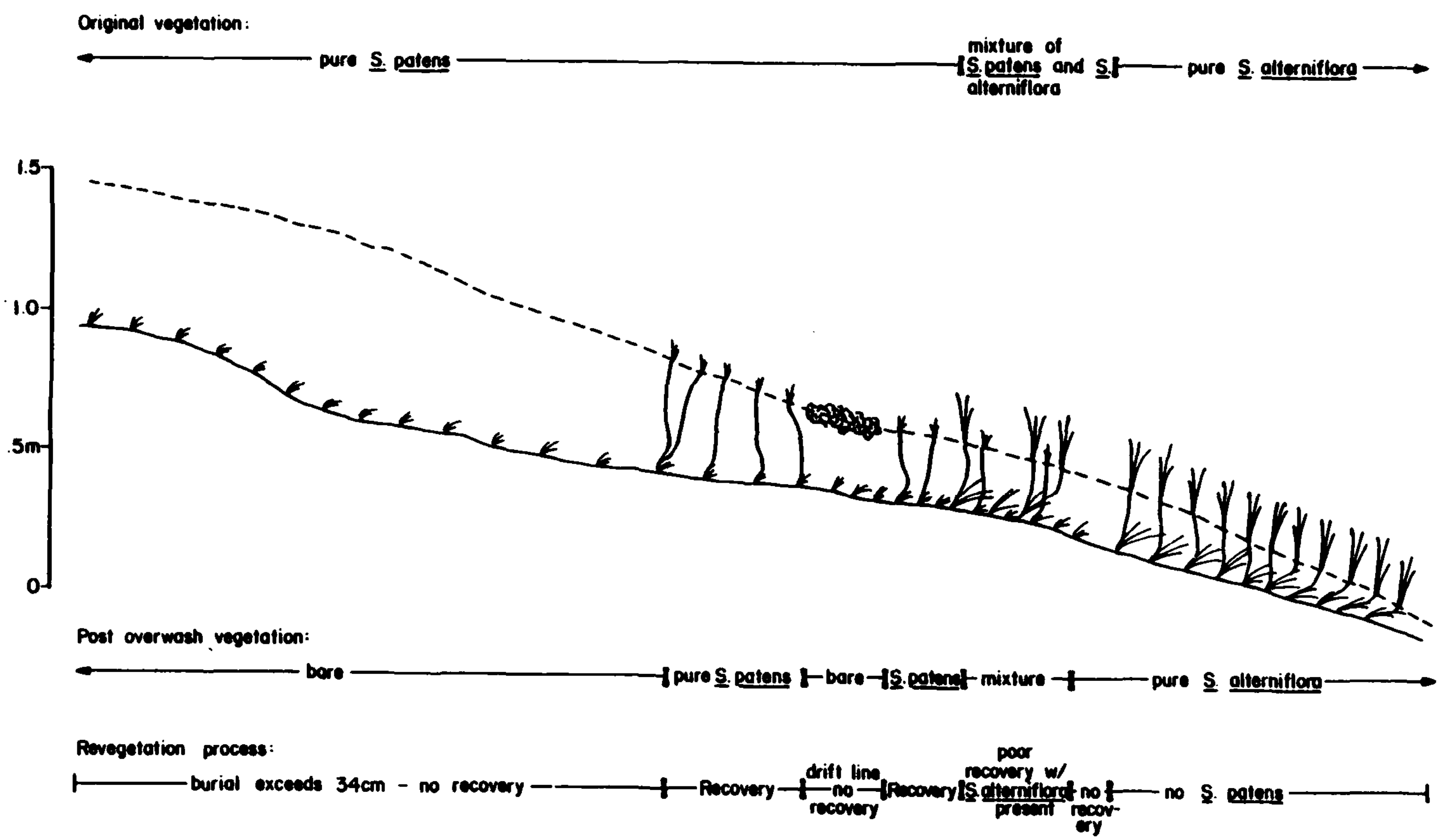


Figure 66. Model for the response of *Spartina patens* (decumbent) to overwash burial.

Comparison of recovered quadrats with quadrats that failed to recover, using site 1 quadrats that were buried by less than 22 centimeters of sand, showed that burial recovery for *Spartina alterniflora* is related to initial (preoverwash) elevation, initial cover and density of *Spartina alterniflora*, and final cover and density of *Spartina patens* in the same quadrats (Figs. 67 to 75). Using all quadrats with *Spartina alterniflora* that received less than 22 centimeters of sand burial, there is no linear relationship between burial depth and final cover, initial and final cover, or initial and final density. In 1977 the magnitude of cover and density of *Spartina alterniflora* was highly correlated with elevation, but in 1978 no such correlation was found.

A review of the elevation data for quadrats containing *Spartina alterniflora* at site 1 in 1977 and 1978 appears in Figure 76. In both 1977 and 1978, *Spartina alterniflora* cover and density were highly correlated (1977, $r = 0.837$, $P < 0.01$; 1978, $r = 0.807$, $P < 0.01$). A comparison of the two regression lines, using a t-test, showed that the slopes of the regression lines are highly significantly different ($P < 0.01$). Multiple regression analysis was unsuccessfully used in an attempt to develop a predictive model for *Spartina alterniflora* recovery from overwash burial.

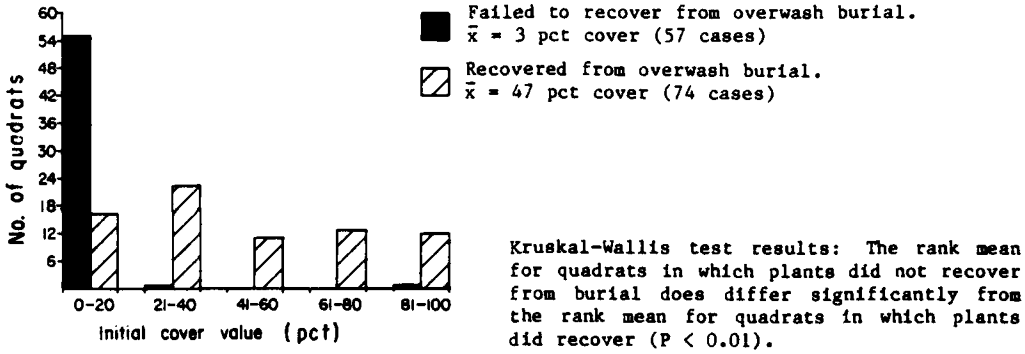


Figure 67. Comparisons of initial cover values for quadrats of *Spartina alterniflora* that recovered and failed to recover from burial.

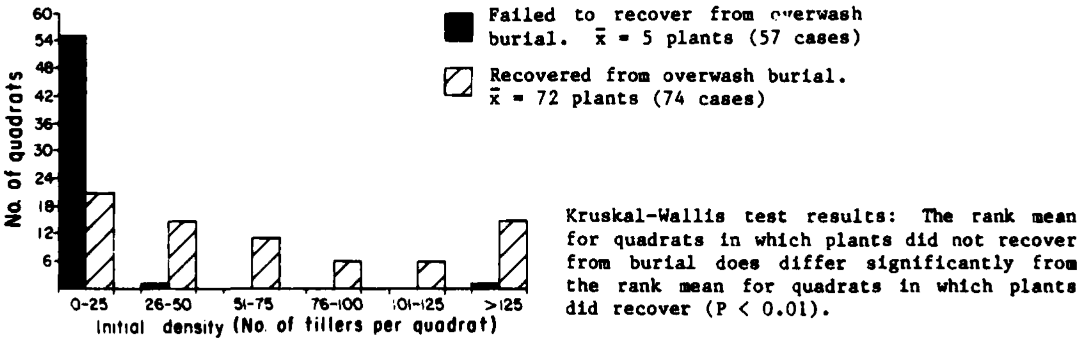


Figure 68. Comparisons of initial density values for quadrats of *Spartina alterniflora* that recovered and failed to recover from overwash burial.

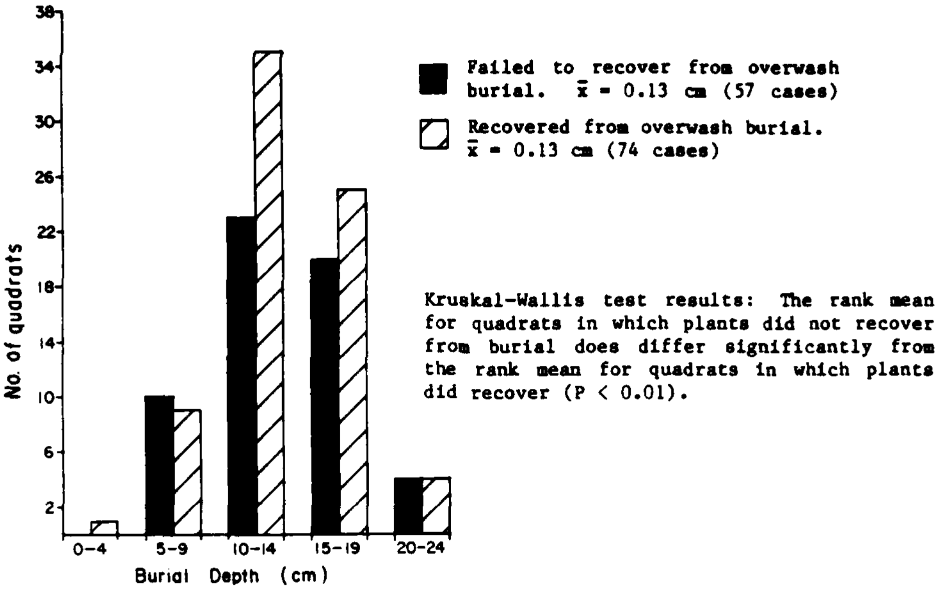


Figure 69. Comparisons of burial depths for quadrats of *Spartina alterniflora* that recovered and failed to recover from overwash burial.

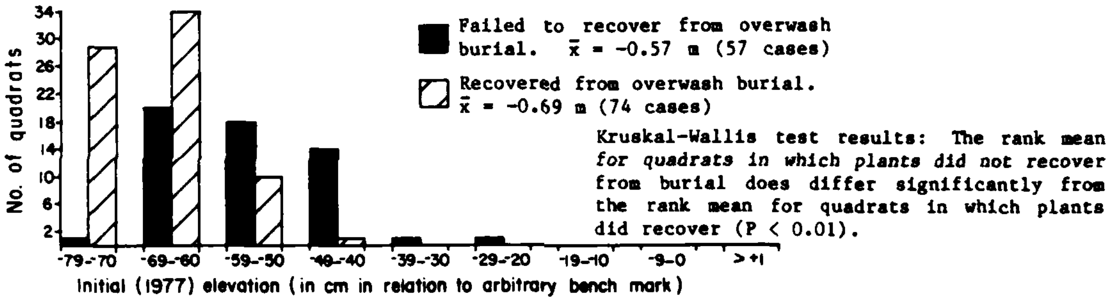


Figure 70. Comparisons of prestorm elevations for quadrats of *Spartina alterniflora* that recovered and failed to recover from burial.

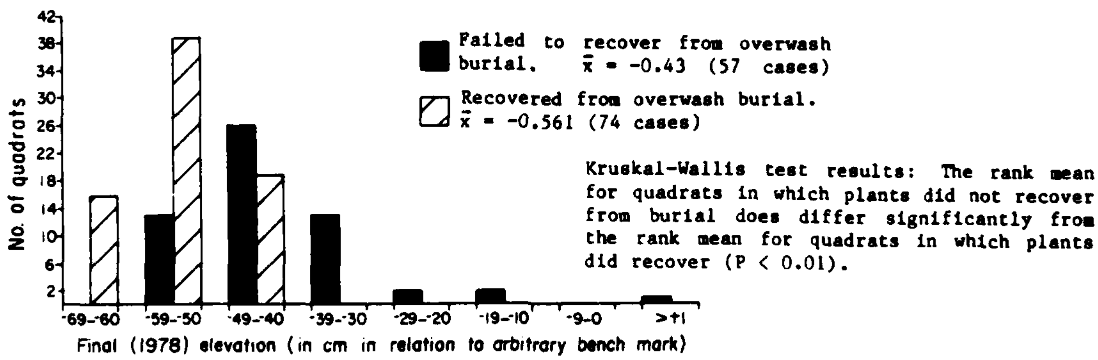


Figure 71. Comparisons of poststorm elevations for quadrats of *Spartina alterniflora* that recovered and failed to recover from burial.

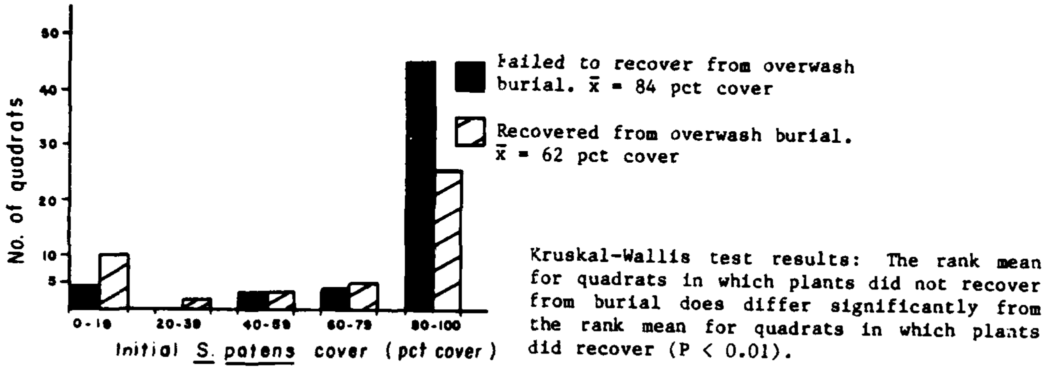


Figure 72. Comparisons of preoverwash cover for quadrats of *Spartina patens* that contained *Spartina alterniflora* which recovered and failed to recover from burial.

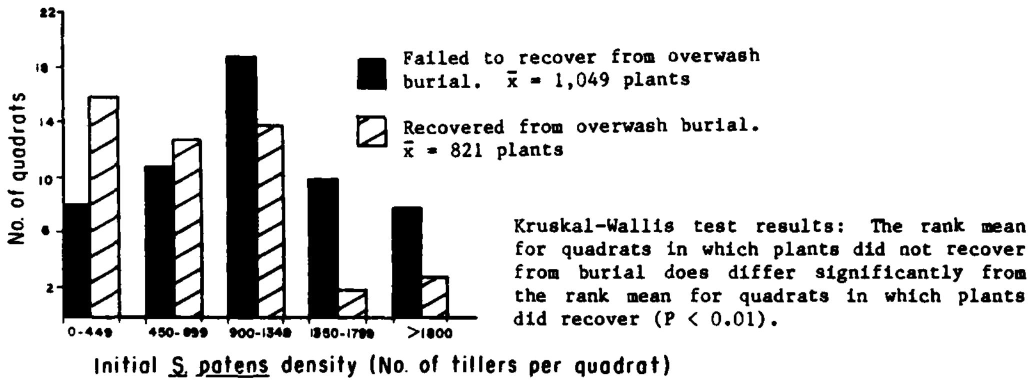


Figure 73. Comparisons of preoverwash density for quadrats of *Spartina patens* that also contained *Spartina alterniflora* which recovered and failed to recover from burial.

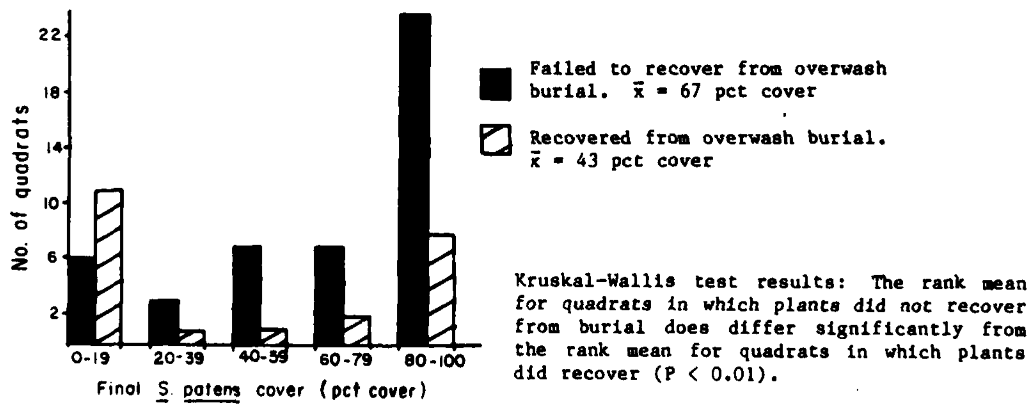


Figure 74. Comparisons of postoverwash cover for quadrats of *Spartina patens* that also contained *Spartina alterniflora* which recovered and failed to recover from burial.

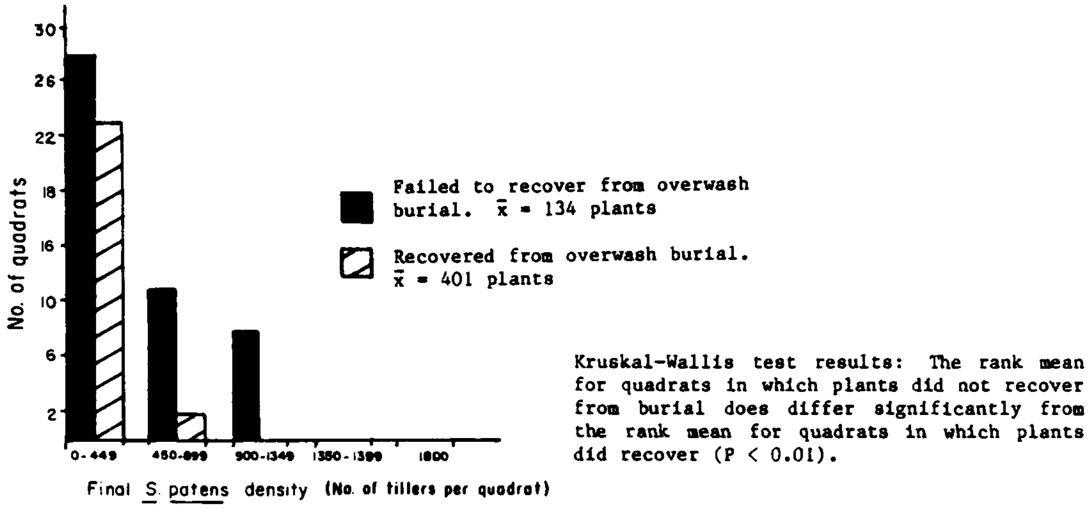


Figure 75. Comparisons of postoverwash density for quadrats of *Spartina patens* that also contained *Spartina alterniflora* which recovered and failed to recover from burial.

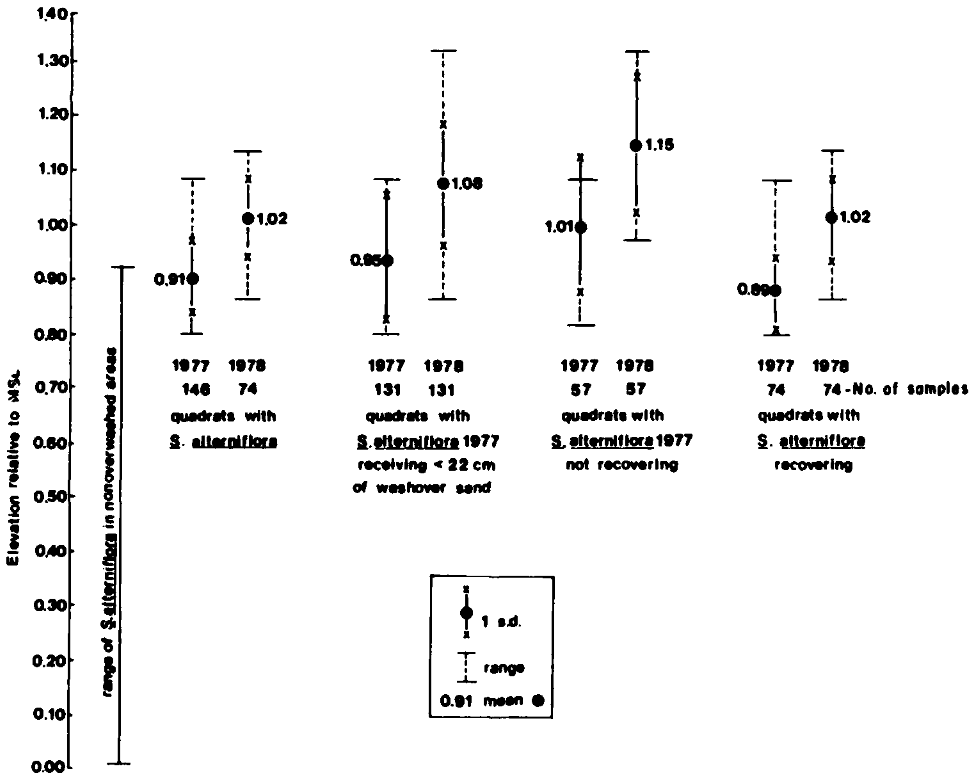


Figure 76. Elevations for quadrats with *Spartina alterniflora* at site 1 fan, 1977 to 1980.

Spartina alterniflora is able to recover from 22 centimeters of overwash burial. Like dune species, but unlike *Spartina patens*, plant recovery for *Spartina alterniflora* is not correlated with burial depth. Individual plants buried by 22 centimeters of sand recover to similar cover and density levels as plants buried by less sand. The elevation range over which *Spartina alterniflora* was found decreased only from 28 centimeters in 1977 to 27 centimeters in 1978. Mean elevation at which *Spartina alterniflora* occurred increased 9 centimeters. Preoverwash density and cover of *Spartina alterniflora* cannot be used to predict postoverwash density and cover. Quadrats with high density and cover did recover better than those with lower density and cover.

As with *Spartina patens*, both cover and density of *Spartina alterniflora* were highly negatively correlated with elevation in 1977. *Spartina alterniflora* grew best at lower elevations over the range of elevations sampled on Nauset Spit-Eastham. In 1978, again no relationship between cover or density and elevation was discovered on analysis. A 27-centimeter elevation range may not have presented enough variation for biomass differences in *Spartina alterniflora* quadrats to be evident.

Cover and density for *Spartina alterniflora*, as for all sampled species on Nauset Spit-Eastham, were highly correlated in both 1977 and 1978. Regression lines for 1977 and 1978 were highly significantly different indicating that individual tiller size was larger in 1978 than in 1977. *Spartina alterniflora* density was highly significantly reduced from 1977 to 1978 at site 1 fan, while *Spartina alterniflora* cover for the entire site actually increased. *Spartina alterniflora*, while unable to recover from the high burial depths (up to 33 centimeters) from which *Spartina patens* can recover, appears to be stimulated by sand burial. *Spartina alterniflora*, annually buried by sediments borne by the tides, has, through time, been under selection pressure to grow through these sediments (recorded as high as 20 centimeters per year; Ranwell, 1975).

Like *Spartina patens*, *Spartina alterniflora* recovered best in quadrats that did not contain other plant species. Plant recovery can be determined by elevation alone and not by presence or absence of competing species. A model for *Spartina alterniflora* recovery in site 1 fan appears in Figure 77.

(c) Discussion. Unlike the dune community, the salt-marsh study areas offered only a limited range of possible marsh situations affected by overwash burial. A wide variety of salt-marsh species and elevations was considered when sites were initially selected on Nauset Spit-Eastham. All three sites sampled on Nauset Spit-Eastham had well-developed salt marshes in 1977. Site 1, which had first overwashed in 1972, had large sections of pure *Spartina patens* and *Spartina alterniflora*. There was also a substantial marsh area with a mixture of species (*Spartina patens*, *Spartina alterniflora*, *Salicornia virginica*, *Limonium nashii*, *Puccinellia maritima*, and *Suaeda maritima*) found near the interface between the high and low marsh. Site 2 was a highly diversified salt marsh with very irregular topography created by mosquito ditching. Two species (*Juncus gerardi* or black grass and *Salicornia europaea* or glasswort), not present in other sites, were present in site 2. Site 3 was also a unique area on Nauset Spit-Eastham with substantial populations of *Plantago maritima*.

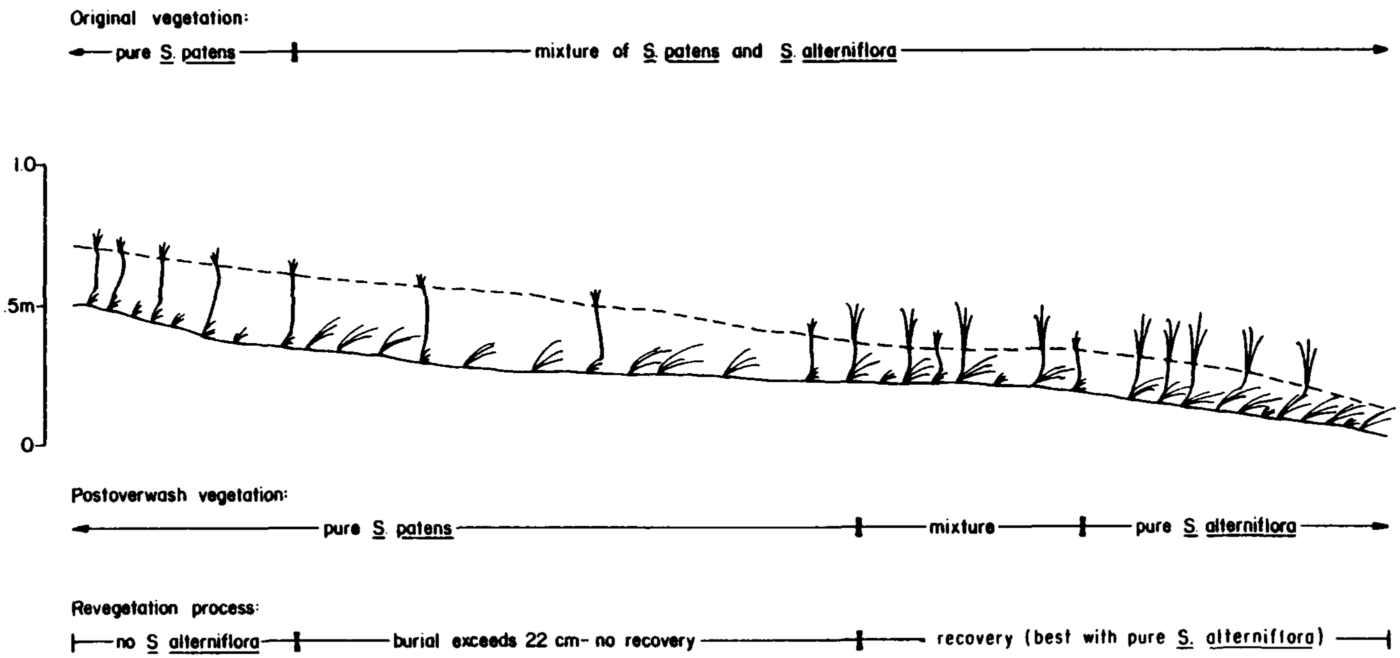


Figure 77. Model for the response of *Spartina alterniflora* to overwash burial.

The storm in February 1978 deposited sand on all three salt-marsh areas. All but 25 quadrats in site 1 fan were buried by washover sand. These 25 quadrats were subsequently buried by 6 to 21 centimeters of sand due to reworking of the washover fan surface by tidal and wind activity. Site 2 was covered by 20 to 50 centimeters of washover sand, but overwash continued through late June during spring tides. In areas where overwash continued into the growing season, salt-marsh vegetation did not recover. All of the salt marsh in site 3 was buried by greater than 34 centimeters of washover sand. Salt-marsh vegetation on Nauset Spit-Eastham did not recover from more than 33 centimeters of sand burial in 1978.

In 1977, seven salt marsh species were found at site 1 fan (Table 27); *Spartina patens* and *Spartina alterniflora* accounted for 81.6 percent of the I.V. In 1978 these species were the only salt-marsh plants found at the site. *Salicornia virginica* had grown through as much as 10 centimeters of washover sand in other areas, but did not recover from burial in site 1. Both *Spartina patens* and *Spartina alterniflora* were able to recover from low level overwash burial. In 1977, 16 percent of the fan buried by less than 34 centimeters of washover sand was revegetated; in 1978, 40 percent was unvegetated. Salt-marsh areas buried by greater than 34 centimeters of washover sand did not recover and were colonized as new substrate by drift-line vegetation. The I.V. of *Spartina alterniflora* increased by 95 percent, while *Spartina patens* increased by only 3 percent. Overwash increased the elevation in site 1 fan. Much of the area, however, remained intertidal and able to support a salt-marsh community.

Table 27. Importance values of species in areas of site 1 fan that received less than 34 centimeters of washover deposition.

Species	Quadrats with plants that recovered (pct)	I.V. 1977	Change (pct)	I.V. 1978
Distichlis spicata	0	0.7		0.0
Limonium nashii	0	9.2		0.0
Puccinellia sp.	0	16.5		0.0
Salicornia virginica	0	24.5		0.0
Spartina alterniflora	91	52.4	+95	102.1
Spartina patens	72	192.3	+3	197.9
Suaeda maritima	0	4.4		0.0

(3) Other Species. The species comprising the majority of plant communities on a northeast barrier beach that are affected by overwash activity were represented in the 2,567 quadrats surveyed on Nauset Spit-Eastham. Other species, less frequently affected by overwash or rarely found on Nauset Spit-Eastham, were observed on North Beach during the field season (1978) following major overwash activity (Table 28). Ten additional species were found that are able to recover from more than 10 centimeters of overwash sand deposition. Principal among these species were the shrubs, *Rosa rugosa* (65 centimeters) and *Myrica pensylvanica* (45 centimeters), which are frequently found on dunes

Table 28. Plants that recovered from overwash after 1 year.

Species	Max. recorded burial depth (cm)	Species	Max. recorded burial depth (cm)
Ammophila breviligulata	59.0	*Salicornia virginica*	10.0
Artemisia stelleriana	53.0	*Scirpus americana*	30.0
Baccharis halimifolia[1]	54.0	*Solidago sempervirens*	56.0
Juniperus virginiana[1]	75.0	*Spartina alterniflora*	30.0
Lathyrus japonicus	43.0	*Spartina patens* (upright)	42.5
Limonium nashii	10.0	*Spartina patens* (decumbent)	33.0
Myrica pensylvanica[1]	45.0	*Teucrium canadense*	25.0
Rosa rugosa[1]	65.0	*Typha latifolia*	20.0

[1]Shrub, not completely buried by overwash deposit.

NOTE.—Data from the summer of 1978. *Ammophila breviligulata*, *Artemisia stelleriana*, *Lathyrus japonicus*, *Solidago sempervirens*, *Spartina alterniflora* and *Spartina patens* data from 1977-78 sampled plots. Other depths selected from washover deposits are not within a study area. All recovered burial depths should be taken as low values.

that continue to accrete at a high annual rate. Other shrubs, *Baccharis halimifolia* (groundsel tree) (54 centimeters) and *Juniperus virginiana* (red cedar) (75 centimeters), found in the stable zone between the dune community and the high marsh community on many northeast barrier beaches, were surprisingly able to recover from high levels of burial. A total of 14 species of flowering plants and 1 gymnosperm were able to recover from 10 centimeters or more of overwash burial at the Nauset Spit (Nauset Spit-Eastham and North Beach) after 1 year.

5. Colonization of Washovers.

a. Introduction. During major storms, overwash surges transport sediment across the entire barrier with deposition in the adjacent lagoon. These deposits represent new supratidal and intertidal environments that may be colonized by vegetation and are important in landward barrier migration. On Nauset Spit-Eastham, almost 2 hectares of new substrate was emplaced along the back barrier margin as a result of the February 1978 storm.

Washover sand is more often deposited on previously vegetated surfaces. After storms, sand-dune vegetation not eroded by overwash surges can recover from burial. *Ammophila breviligulata* plants, buried by as much as 67 centimeters of sand, recovered rapidly, early in the growing season. Overwash and aeolian burial actually lead to an increase in *Ammophila breviligulata* biomass. Salt-marsh plants buried by shallow deposits can also recover, although washover deposition in the northeast often exceeds plant recovery capability. During the February 1978 storm, sand deposits as deep as 165 centimeters accumulated on old marsh surfaces, resulting in large, barren, flat washovers on Nauset Spit-Eastham.

An analysis of historical aerial photography (see Sec. IV) suggests that these initially barren areas are rapidly colonized by either salt-marsh or sand-dune vegetation. Photos taken soon after the 1938 hurricane showed large barren washovers along North Beach. These features were still evident in 1952 but were covered by sand dunes and salt marshes. In December 1972 a

small washover fan was formed on the salt marsh to the lee of the Nauset Spit-Eastham dune line; marsh vegetation did not recover from burial. Three years later, small dunes (75 centimeters high) had formed in the proximity of drift lines.

While the revegetation process on washover fans has not previously been studied, colonization of the beach-backshore has been the subject of several studies. Since the beach-backshore is an unstable area, the species assemblage has not been regarded as a defined community. In many studies of community succession in the coastal zone, however, the beach-backshore has been included as the earliest, least developed sere (Gimingham, Gemmet, and Greig-Smith, 1948; Vose, Powell, and Spence, 1957; Laing, 1958; Olson, 1958; Willis, et al., 1959; Morton, 1974; van der Valk, 1974; Ranwell, 1975; Chapman, 1976).

The importance of drift lines in the initiation of dune-building processes was recognized historically (Cowles, 1899) and has since been repeatedly stressed (Gimingham, Gemmet, and Greig-Smith, 1948; Robertson and Gimingham, 1951; Salisbury, 1952; Laing, 1958; Olson, 1958; Tansley, 1968; Ranwell, 1975; Chapman, 1976). The characteristic linear form of barrier dune ridges at a spit terminus has been attributed to the form of drift lines (Godfrey, 1977).

Details concerning the ecology of the beach-backshore have been numerous, but sketchy. Many studies have considered the area without focusing on organic debris; others have examined drift-line debris without considering its role in the overall community development of barrier beaches. Species lists have been made for east (Harshberger, 1916) and west coast (Barbour, DeJong, and Johnson, 1976) beaches in the United States. Extensive data are also available in Britain (Gimingham, 1964; Tansley, 1968).

There are three ways in which barren washovers can be colonized: (1) plants on the previous surface can grow through the washover deposits; (2) remnant, or peripheral, vegetated areas can expand into barren deposits by rhizome extension; or (3) new propagules (both seeds and plant fragments) can become established in an area. Colonization of washover fans by the latter two means should be considered primary succession because sand deposition is generally so great that the original substrate only tangentially affects vegetation.

b. Recovery. On Nauset Spit-Eastham, four major dune species were able to recover from high levels (up to 67 centimeters) of overwash burial. Dunes, however, are generally eroded by storms to depths below the vegetated surface. Plants in site 1 throat and the 1972 washover in site 1 fan were completely eroded during the February storm. At site 3, two-thirds of the dunes were subjected to erosion; remaining dune plants, however, recovered to biomass levels equal to or in excess of prestorm levels.

In the salt marsh, deposition occurred without erosion. Both principal marsh species, *Spartina patens* and *Spartina alterniflora*, were able to recover from low-level burial. Plants at sites 2 and 3, however, were buried by greater volumes of sand; only plants at site 1 were able to recover. Approximately 20 percent of site 1 was populated in 1978 by marsh grasses recovering from overwash. Much of the remaining area was either buried by depths in excess of 33 centimeters (maximum recovery depth of *Spartina patens*) or had not been vegetated by either species in 1977.

c. Rhizome Extension.

(1) Dunes. All of the major plant species on Nauset Spit-Eastham are rhizomatous and rely primarily on vegetative reproduction. *Ammophila breviligulata* has the capability of extending its rhizomes both vertically in response to sand burial and horizontally to colonize new areas. Measuring the rate of natural sand accretion in North Carolina, Woodhouse and Hanes (1967) documented that *Ammophila breviligulata* can recover from as much as 120 centimeters of burial in 1 year. Ranwell (1975) stated that while *Ammophila breviligulata* can recover from 90 centimeters of gradual burial, the plant would probably be unable to recover from an instantaneous deposition of 90 centimeters of sand. Overwash activity may, in low dune areas, bury *Ammophila breviligulata* by large amounts of sediment (sometimes approaching 1 meter).

To test the ability of *Ammophila breviligulata* to recover from sand burial, a 55-gallon drum, with open ends, was placed over a healthy stand of *Ammophila breviligulata* on an accreting dune in early April 1979. From inspection of the base of tillers, it appeared that approximately 25 centimeters of sand had naturally accumulated during the previous winter. Thirty-eight tillers were present in the area that was experimentally buried. The barrel was filled to the top (90 centimeters), and sand was mounded around the base. The first tiller visible on the surface was recorded 5 weeks after the beginning of the experiment (Fig. 78). Vertical rhizomes extended through a total of 115 centimeters of sand in 35 days for a rate of 3.3 centimeters per day.

Measurements taken during the height of the growing season have shown that *Ammophila breviligulata* rhizomes can grow horizontally as much as 2 centimeters per day (Brodhead and Godfrey, 1979). The *Ammophila* front can expand seaward in favorable areas at a rate of 4 to 5 meters per year. Rhizome extension into washovers was not visible during the first growing season after overwash. Since buds along rhizomes do not break dormancy until the year following their formation, there may be no visible evidence of plant growth, although rhizomes may exist below the sand surface. Excavations of dunes adjacent to site 1 revealed that *Ammophila breviligulata* plants had extended as much as 2 meters into the washover fan.

During the second growing season (1979), the location of *Ammophila breviligulata* was recorded in relation to the remnant dune line. An 800-meter transect was established along the back side of the Nauset Spit-Eastham dune line paralleling an off-road vehicle trail. At a 2-meter interval, the location of the marshward edge of the established dune vegetation was noted, and the distance of newly emergent plants from the dune edge was recorded. Plants were excavated to distinguish tillers resulting from rhizome extension from fragments regenerating in drift lines. Only a few tillers were evident in the road in 1978; these plants were undoubtedly from rhizomes that had extended into the road before the 1978 storm. *Ammophila breviligulata* tillers in 1979 were located as far as 4.6 meters from the rhizome origin, but these tillers had not formed a closed population 2 years after the storm. *Ammophila breviligulata* tillers, however, had become well established on washover substrate above former salt-marsh vegetation. A map of the outgrowth of dune vegetation from the western edge of the dune line shows that the greatest expansion occurred along areas downwind of washovers (Fig. 79). The prevailing, sand-transporting northwest winds added sediment to the dune line southeast of washovers.

Figure 78. Growth of *Ammophila breviligulata* through 90 centimeters of artificial burial.

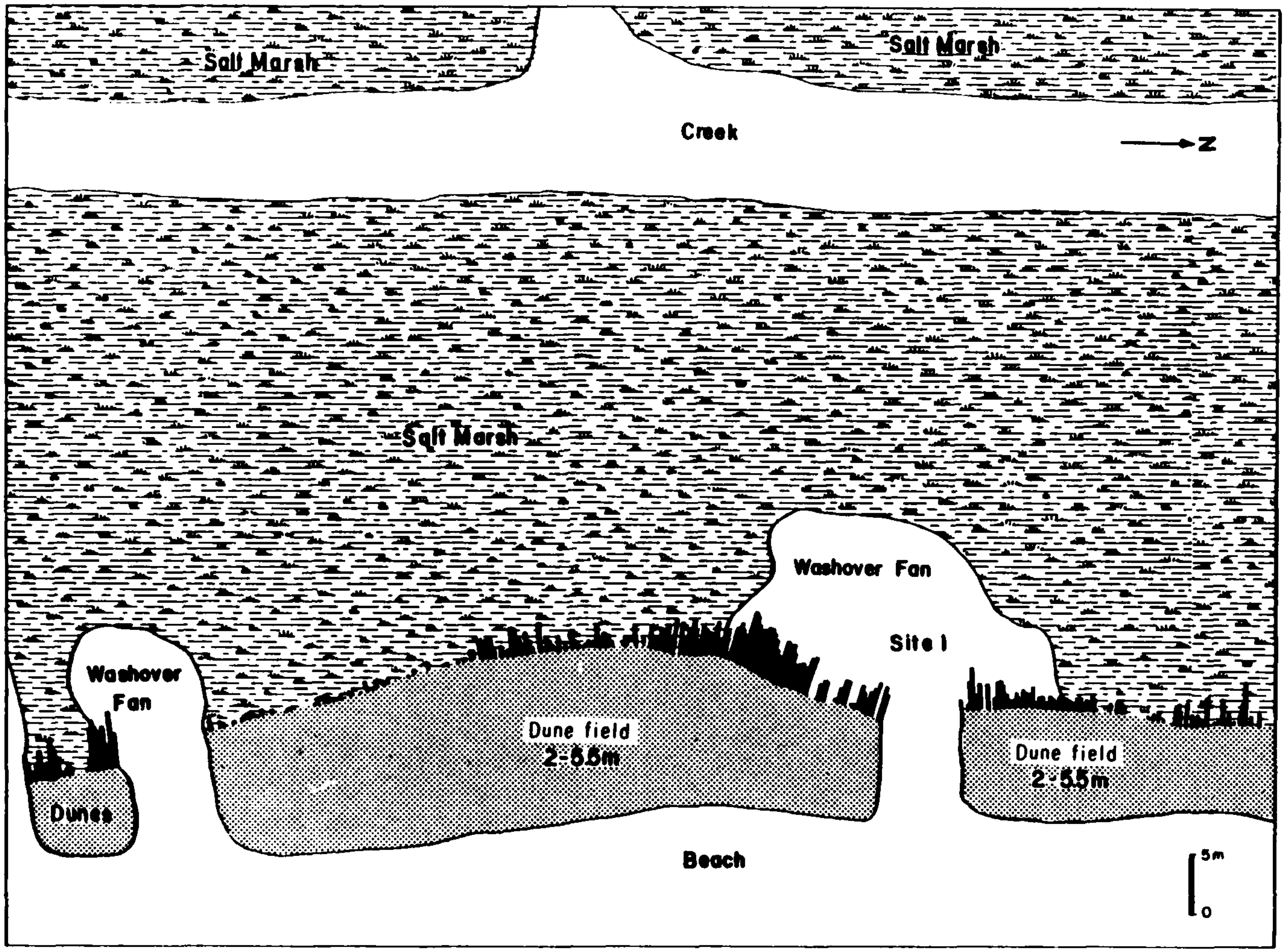


Figure 79. Outgrowth of dune line following the 1978 storm. Note rapid regrowth of back dunes adjacent to washovers due to influx of new sand.

The three other major dune species (*Solidago sempervirens*, *Artemisia stelleriana*, and *Lathyrus japonicus*) on Nauset Spit-Eastham are also able to expand both vertically and laterally by rhizome extension, although not to the same degree as *Ammophila breviligulata*. Individual plants of *Solidago sempervirens* that recovered from burial (of about 40 centimeters) were as much as 40 centimeters larger in diameter the year after overwash. *Artemisia stelleriana* plants expanded less rapidly, approximately 10 to 20 centimeters per year. *Lathyrus japonicus* can freely expand by rhizome extension; plants in the dunes may be several meters apart and connected by rhizomes. During the 1978 and 1979 seasons, *Lathyrus japonicus* did not, however, appear to expand into uncolonized substrate on Nauset Spit-Eastham.

(2) Salt Marsh. Both *Spartina patens* and *Spartina alterniflora* commonly colonize new substrate by rhizome extension. Redfield (1972), studying the development of the salt marsh behind Sandy Neck in Barnstable, Massachusetts, over a 12-year period, calculated that *Spartina alterniflora* would have to colonize new substrate at a rate of 1.3 meters per year to produce the salt-marsh enlargement evident in dated peat deposits. He reasoned that *Spartina alterniflora* rhizome extension alone was not sufficient to account for this rate of expansion. Colonization by new propagules (either seeds or fragment regeneration) would be necessary for such rapid salt-marsh establishment. Over hundreds of years, new marshes formed at the leading edge of the sandflats and were eroded several times before a permanent, continuous marsh was formed.

On Nauset Spit-Eastham, there were no salt-marsh plants unaffected by burial contiguous to washovers in 1978. *Spartina patens* and *Spartina alterniflora* plants that were able to recover did so by vertical rhizome extension through washover deposits. These plants did not expand laterally the first year.

Stands of *Spartina patens* that had recovered in 1978 enlarged by rhizome extension the following year. There was no evidence from quadrat data that *Spartina alterniflora* had expanded by rhizome extension. Vegetation maps of site 1 in 1977, 1978, and 1979 indicated that *Spartina alterniflora* populations expanded 1 meter into new substrate at lower elevations. *Spartina patens* patches expanded vigorously on all fronts, extending as far as 50 centimeters per year from the 1978 plants. Elevation information indicated that *Spartina patens* was present in quadrats at higher elevations in 1979 than in 1978 or 1977. In 1979, 34 quadrats, which were not vegetated in 1978, were colonized by *Spartina patens* through rhizome extension. Mean elevation for these quadrats was 8 centimeters higher than the mean of recovering quadrats; these higher elevations were within the range of *Ammophila breviligulata*.

d. Seed and Fragment Regeneration. The depth of 1978 washover deposition on Nauset Spit-Eastham generally exceeded levels from which marsh vegetation could recover. Sand dunes were generally eroded by storm surges, except where low or initially building. Most washovers on Nauset Spit-Eastham were also too far removed from remnant dunes or recovering salt marshes to be affected by rhizome extension. The most effective means of colonizing washovers is by the establishment of new vegetation. In all, within sampled sites, 89 quadrats (of a total of 2,567 quadrats) were populated with new plants in 1978. In 1979, following a winter with exceptionally high tides, 298 quadrats had new plants.

Two types of new propagules become established on washovers: seeds and plant fragments. New species of flowering plants colonizing washovers on Nauset Spit-Eastham and North Beach were recorded during 1978 and 1979 (Table 29).

Table 29. Washover species list, Nauset Spit-Eastham.

Species	F[1]	S[2]	1978			1979	
			o[3]	st[4]	b[5]	o[3]	b[5]
Agropyron pungens	x						x
Ammophila breviligulata	x	x	x	x	x	x	x
		x	x	x	x	x	x
Arenaria peploides	x		x	x	x	x	x
Artemisia caudata		x					x
Artemisia stelleriana	x		x	x	x	x	x
		x					x
Atriplex arenaria		x		x	x		x
Atriplex patula		x		x	x	x	x
Cakile edentula		x	x	x	x	x	x
Carex silicea		x		x	x		x
Chenopodium albidum		x					x
Convolvulus sepium		x			x		x
Euphorbia polygonifolia		x	x	x	x		x
Lathyrus japonicus	x		x	x	x	x	x
		x	x	x	x		x
Oenothera biennis		x					x
Panicum virgatum		x		x	x		x
Rhus radicans	x						x
		x					x
Salsola kali		x	x	x	x	x	x
Solidago sempervirens	x			x	x		x
		x					x
Spartina alterniflora		x					x
Spartina patens	x		x		x		x
		x					x
Suaeda maritima		x					x
Xanthium echinatum		x		x	x	x	x

[1]F = regenerated from fragments.

[2]S = seedlings.

[3]o = oceanic drift line.

[4]st = storm drift pile.

[5]b = bay drift line.

Two major factors determine the seedling crop, type, and abundance of plant fragments on washovers each year: winter conditions that distribute propagules and climatic conditions in the late spring and summer months. The February 1978 storm swept massive areas of Nauset Spit-Eastham and North Beach clean of storm debris, leaving few obstacles to trap seeds and fragments. Following the storm, spring tides on the bay side deposited large amounts of drift material progressively lower on the edges of washovers. Large numbers of drift seeds settled out to the lower parts of these drift lines. Wind-distributed sand buried the debris.

The weather was particularly wet and cool in spring 1978. In April, May, and June, 279 millimeters of precipitation fell at the Chatham Weather Station, located 12 miles south of Nauset Spit-Eastham. Temperatures averaged 6° Celsius in April, 11° Celsius in May, and 17° Celsius in June 1978 (Fig. 80). Eleven species of flowering plants germinated on washovers in 1978 (Table 29). Most new plants were located in large clumps of debris or in well-organized drift lines. The first seedlings noted on Nauset Spit-Eastham were of *Cakile edentula* (5 April 1978). The last day with freezing temperatures was 10 April. Seeds did not germinate between 3 July and early September 1978, after which all new seedlings did not survive brief fall droughts.

Living plant material torn from the dunes is, in many cases, able to regenerate. All four major dune species on Nauset Spit-Eastham, *Ammophila breviligulata*, *Solidago sempervirens*, *Lathyrus japonicus*, and *Artemisia stelleriana*, can reproduce vegetatively from plant fragments. The February 1978 storm destroyed large sections of dune line, uprooting vast quantities of organic material. In 1978 seven species of flowering plants regenerated from fragments (Table 29).

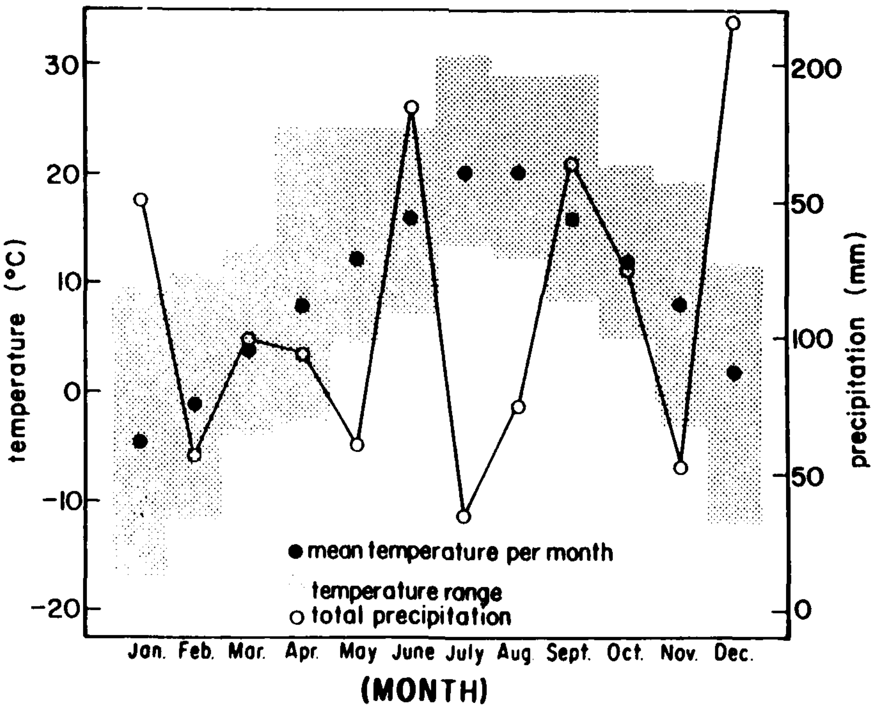


Figure 80. Monthly temperature and moisture values on Cape Cod, 1978.

Wind deflation of washovers and poor dune development resulted in a low elevation profile on the barrier during the first winter after the February storm. Many of the 1978 drift lines had been destroyed as a result of wind and water erosion, and overwash occurred with even marginal winter storms. During one storm in January 1979, all but the highest dunes on Nauset Spit-Eastham were awash, and drift material, laden with seeds and plant fragments, was stranded high in the dunes. In March, permanent drift lines were again laid down on the bay side margins of washover features. Some of these drift lines were deposited either on top of or adjacent to old bay-side drift lines, enlarging and protecting these features. Other drift lines were deposited on barren areas and were similar to 1978 drift lines. High winds during the spring redistributed sediment from the washovers, quickly burying the nearby drift material.

The spring of 1979 was again very wet and cool on Cape Cod, with 274 millimeters of precipitation in April, May, and June, and mean monthly temperatures of 7°, 13°, and 17° Celsius (Fig. 81). New plants in 1979 appeared, not only in organized drift lines, but also in barren areas well removed from spring tides. The first appearance of seedlings (*Cakile edentula*) was on 5 April and again roughly correlated with the last spring frost on 8 April. Seeds did not successfully germinate between 5 June and 21 August. Seeds of 20 species of flowering plants germinated on Nauset Spit-Eastham in 1979 (Table 29). Although few dunes were destroyed by storms in 1979, abundant plant fragments were present in Nauset Spit-Eastham drift lines. Eight species of flowering plants regenerated from fragments (Table 29).

During 1978 and 1979, population data were collected at site 1 fan to determine the relative abundance and mortality of colonizing plant species. Site 1 fan was subdivided into 120 5- by 5-meter plots. Seedlings and regenerating axes were counted early in the spring and biweekly during the field season. Data for 1978 and 1979 appear in Tables 30 and 31.

The most hardy and widespread propagules in both 1978 and 1979 were *Ammophila breviligulata* fragments which regenerated between late April and early June. In April 1978, 9 tillers of *Ammophila breviligulata* were evident within the site; 363 were recorded in June. Increase in axes numbers after 5 June 1978 was due to new bud break along already regenerating axes and not to newly regenerating fragments. By September these axes numbered 352 after peaking in August at 402. Wind deflation of sand caused many shallow-buried fragments to desiccate and die.

Most fragments regenerated early in the season before the summer drought. Deep-buried regenerating fragments seemed to grow to the surface by 15 June. To determine the validity of this observation, 10 fragments of *Ammophila breviligulata* were buried at each of three depths in April 1979: 25, 50, and 90 centimeters. Seven fragments buried at 25 centimeters regenerated within 3 weeks; four fragments buried at 50 centimeters regenerated within 4 weeks; and three fragments buried at 90 centimeters regenerated within 5 weeks (15 May).

The winter overwashes of 1978-79 eroded only a small part of the 1978 drift line at site 1 fan. New drift material with many fragments was deposited at the outer edges of vegetated drift lines. It was not possible to distinguish 1979 fragments from recovering plants at site 1 without excavating the plots. Nearby drift lines, outside permanent sites, were excavated to

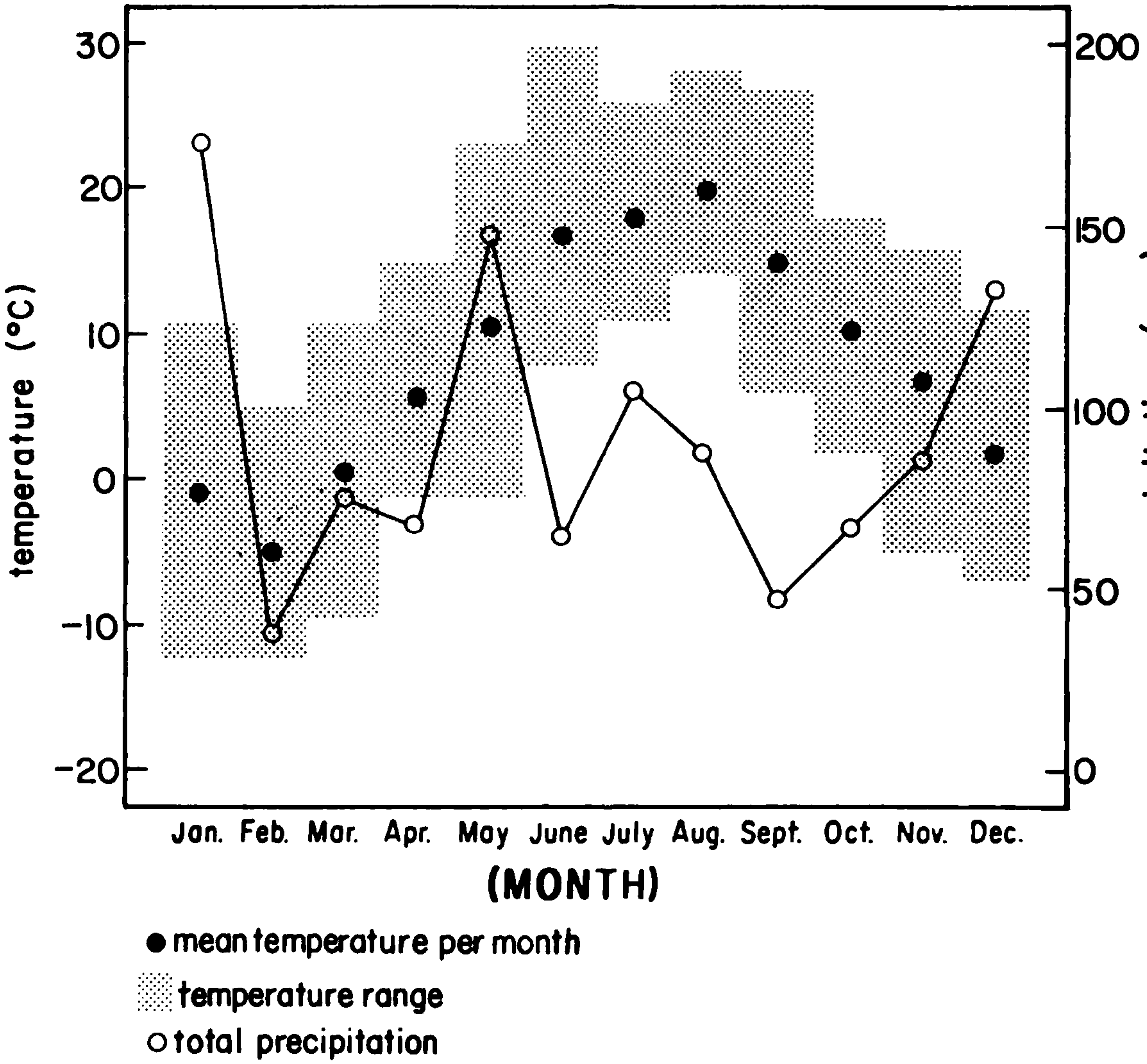


Figure 81. Monthly temperature and moisture values on Cape Cod, 1979.

Table 30. Count of seedlings and regenerating axes for drift-line vegetation at site 1 fan, 1978.

Species	S[1]	F[2]	A[3]	P[4]	23 Apr.	6 May	22 May	5 June	27 June	10 July	24 July	8 Aug.	24 Aug.
Ammophila breviligulata		x		x	9	35	160	363	383	381	400	402	352
	x			x				18	44	54	43	36	32
Arenaria peploides		x		x		2							
Artemisia stelleriana		x		x			35	91	136	'129	172	278	136
Atriplex patula	x		x					1	1	1	11	11	10
Cakile edentula	x		x		72	71	94	160	121	95	90	83	73
Carex silicea	x			x							1	1	3
Lathyrus japonicus		x		x				159	22	104	2	65	45
	x			x				159	152	104	78	65	45
Panicum virgatum	x		x						2	3	3	3	2
Plantago maritima	x			x									
Salsola kali	x		x			4	4	10	4	4	3	3	1
Solidago sempervirens		x		x		1	2	2					
Spartina patens		x		x				9	95	137	154	171	193
Unknown	x								1				
Xanthium echinatum	x		x					3	2	1	8	8	1

[1]S = seedlings.

[2]F = regenerating from fragments.

[3]A = annual.

[4]P = perennial.

Table 31. Count of seedlings and regenerating axes for drift-line vegetation at site 1 fan, 1979.

Species	S[1]	F[2]	5 Apr.	5 June	22 June	6 July	19 July	1 Aug.	24 Aug.	5 Sept.	20 Sept.
Agropyron pungens		x				3	3	3	3		
Ammophila breviligulata	x			254					323		
		x	161	1,639					2,129	7,298	>10,000
Arenaria peploides		x		30					7	51	
Artemisia stelleriana	x				16	18	12	24	156		
		x	30	65					49	1,120	
Atriplex patula	x			86	74	82	57	34	19		
Cakile edentula	x		12	1,218	1,267	1,127	1,072	732	386	3,807	
Chenopodium albidum	x				1	1	1	2	3		
Convolvulus sepium	x			2	1	1	1	1	1		
Euphorbia polygonifolia	x			1		10	4	16	10		
Lathyrus japonicus	x			176	119	117	155	162	144	433	
		x		2	2	2	2	2	2	4	
Limonium nashii	x						14	6	9		
Oenothera biennis	x				1	1	3	3	4		
Panicum virgatum	x			7	7	5	6	3	3		
Plantago maritima	x			1	1	1	1	3	2		
Rosa rugosa	x			1							
Salicornia virginica	x					4	2	1	3		
Salsola kali	x			55	59	41	30	20	11	2	
Solidago sempervirens	x			74	76	74	61	53	45	1	
		x		25					11	9	
Spartina alterniflora		x		12							
Spartina patens		x		261					1,040		
Suaeda maritima	x			4	5	7	5	1	4	1	
Unknown	x			2	3						
Xanthium echinatum	x				4	4	1	2	1	6	

[1] S = seedlings.

[2] F = regenerating from fragments.

calculate the percentage of new, recovering fragments. Forty percent of the *Ammophila breviligulata* axes in these drift lines were newly established in 1979 from fragments. Site 1 fan had 161 *Ammophila breviligulata* axes in April 1979, most of which were previously regenerating fragments. The number increased steadily during the summer to 2,129 in late August.

Seedlings of *Ammophila breviligulata* were also found in site 1 during both 1978 and 1979. Reports vary in the literature concerning the importance of seedlings to *Ammophila breviligulata* colonization and population dynamics. Seedlings have been reported to be rare in the fixed dune community and unimportant in the colonization of new areas (Laing, 1958). Other reports have suggested that there are seed years when large numbers of seedlings survive and genetic diversity increases (Tansley, 1968; Huiskes, 1977, 1979).

In 1978, 18 seedlings were located in site 1 on 5 June. New seedlings appeared until 10 July. Throughout July and August, seedling counts were made weekly (Table 32). Most seedlings died during late July and August, presumably from drought. Van der Valk (1974) reported that the main cause of seedling mortality was sand deflation. Although the site was unprotected from southwest and northwest winds, there was no major wind erosion during the summer.

Table 32. Measurements of *Ammophila breviligulata* seedlings, 1978.

Date	Avg. No. of leaves			Length of longest leaf			No. of plants living		
	Ocean	Bay	Storm	Ocean (cm)	Bay (cm)	Storm (cm)	Ocean	Bay	Storm
16 June	-- [1]	2.3	--	--	9.9	--	--	20	--
29 June	1.8	2.4	2.0	14.5	11.1	12.0	20	19	20
14 July	2.1	2.3	1.9	16.1	10.8	13.4	17	18	19
28 July	1.7	2.4	2.1	15.7	8.9	16.0	15	15	18
11 Aug.	2.2	2.2	2.0	19.4	13.0	18.2	15	14	16
21 Aug.	2.3	2.3	2.4	20.7	16.3	18.9	14	12	16
16 Sept.	--	--	--	--	--	--	14	12	14

[1] Not measured.

To determine the survival rate of *Ammophila breviligulata* seedlings on Nauset Spit-Eastham, 20 plants were chosen in early June 1978 at each of three habitats: ocean beach, washover flat, and bay-side drift line. For each plant, the number of leaves and the length of the longest leaf were recorded weekly. The greatest density of *Ammophila breviligulata* seedlings occurred in bay-side drift lines where occasional groups of seedlings were found associated with a displaced, intact flowering culm. Plant growth was significantly greater on the ocean beach than on either the washover fan or in the bay drift line ($P < 0.01$). By the end of the summer, 14 plants survived at the ocean site, 14 on the washover fan, and 12 in the drift line. All plants were labeled with the hope of determining the overwinter survival rate. During the winter, both the ocean and washover sites were completely eliminated by storms. Although sections of the bay drift line in site 1, which had 20 labeled seedlings, were unaffected by storms, seedlings did not live through the winter. The overwintering unit typical of *Ammophila breviligulata* had not been evident on any of these seedlings during the fall of 1978. While seedlings in 1978 were occasionally located on Nauset Spit-Eastham, none were known to survive their first winter.

In early May 1979 thousands of grass seedlings were present on Nauset Spit-Eastham. Since total counts for seedlings at site 1 were infeasible, only eight 5- by 5-meter plots of *Ammophila breviligulata* were chosen for study. Seedling counts were as follows: 202 on 5 June, 203 on 22 July, and 189 on 24 August. In October most of these seedlings were between 20 and 30 centimeters tall, and perennating units were evident with the onset of winter.

The three other species commonly found in local dune communities, *Artemisia stelleriana*, *Lathyrus japonicus*, and *Solidago sempervirens*, all regenerated from fragments and were found in site 1 during both 1978 and 1979. Forty-six *Artemisia stelleriana* fragments regenerated in 1978 at site 1. Ten fragments of *Artemisia stelleriana* found in Nauset Spit-Eastham drift lines were planted in sand at the University of Massachusetts greenhouse in February 1978. All 10 fragments regenerated within 3 weeks and flowered within 12 weeks. Individual *Artemisia stelleriana* plants increased to 65 in 1979. Six

seedlings of *Artemisia stelleriana* were also found on the site in May 1979 and survived the summer. In late August, hundreds of *Artemisia stelleriana* seeds germinated near parent plants, but were killed by sand burial early in the fall.

While only two fragments of *Lathyrus japonicus* regenerated in 1978, 157 *Lathyrus japonicus* seedlings were present within the site in 1978. All these plants were monitored the following year. The two asexually produced plants survived the winter, but all the seedlings died. New seedlings (164) were produced in 1979, and no new fragments regenerated.

In 1978 only two fragments of *Solidago sempervirens* regenerated at site 1; both these plants survived the winter. In 1979, an additional 25 fragments regenerated and 76 seedlings were present at the site. Many of these seedlings (31) germinated at intertidal elevations and were killed by spring tides in July.

The other major species to regenerate from fragments at site 1 was *Spartina patens*. In 1978, 193 tillers of *Spartina patens* were present in site 1, all from fragment regeneration. Several groups of tillers were eroded during the winter, and several new drift piles were established in 1979, with a total of 1,040 *Spartina patens* tillers. There are two reported varieties of *Spartina patens* in New England: *Spartina patens* decumbent and *Spartina patens* var. *monogyna*. Decumbent *Spartina patens* is a thin-bladed, early flowering grass that establishes mats of vegetation in the high marsh. *Spartina patens* var. *monogyna* is erect, somewhat taller, later flowering, and grows in the dune-marsh ecotone in sandy substrate. Inspection of the *Spartina patens* population indicated that both varieties were present at site 1. Two groups of plants flowered in 1979 and coincided with *Spartina patens* var. *monogyna* flowering.

Early in 1978 it became evident that most new plants on washover features were associated with drift material. Vegetation sampling in August 1978 indicated that 85 percent of quadrats with seedlings or regenerating fragments also contained surface drift debris. Excavation of plants outside sampled areas revealed that virtually all new plant roots were associated with decaying organic material.

Chapman (1976) described two types of drift lines along the British coast: one located on the ocean beach, composed primarily of algae and diverse vascular plant tissue with a restricted flora, and another located at the upper reaches of the salt marsh, composed of marsh-grass detritus with a more diversified flora. Following the February 1978 storm, three types of drift lines with three distinct floras were present on Nauset Spit: (1) storm drift piles, (2) oceanic drift lines, and (3) bay drift lines.

(1) Storm Drift Piles. Overwash surges tore large sections of organic material from dune and shrub communities. This debris collected in masses along Nauset Spit-Eastham (Fig. 82). Often a displaced shrub (*Myrica pensylvanica*, *Rosa rugosa*, or *Prunus maritima*) or remnants of the four houses that were destroyed during the February 1978 storm acted as a nucleus, which caught other material carried by storm waves. Occasionally, uprooted dune vegetation, primarily *Ammophila breviligulata*, was displaced by overwash in a sizable unit and accumulated passing debris. Dimensions of storm drift piles

Figure 82. Storm drift piles on Nauset Spit-Eastham.

varied from small tangles of *Ammophila breviligulata* rhizomes and tillers 30 to 40 centimeters in diameter to shrub collections several meters in length. After the February storm, it was difficult to assess the number of these piles, since some piles were surficial while others were completely buried by washover deposits. Wind deflation left many of these drift piles projecting 50 to 75 centimeters above the sand surface so that morphologically they appeared as small dunes.

Storm drift piles were sparsely vegetated and supported 13 species of flowering plants on Nauset Spit-Eastham in 1978 (Table 29). Few seeds were present among the organic material, and those seeds that germinated frequently died by midsummer. These drift piles were composed of coarse organic material which is poor in moisture retention. Species lists were compiled for all three types of drift lines at 19 locations on Cape Cod in 1978 and 1979 (Fig. 83). Twenty-four species of flowering plants were found in storm drift piles at six locations on Cape Cod in 1978 and 1979 (Tables 33 and 34).

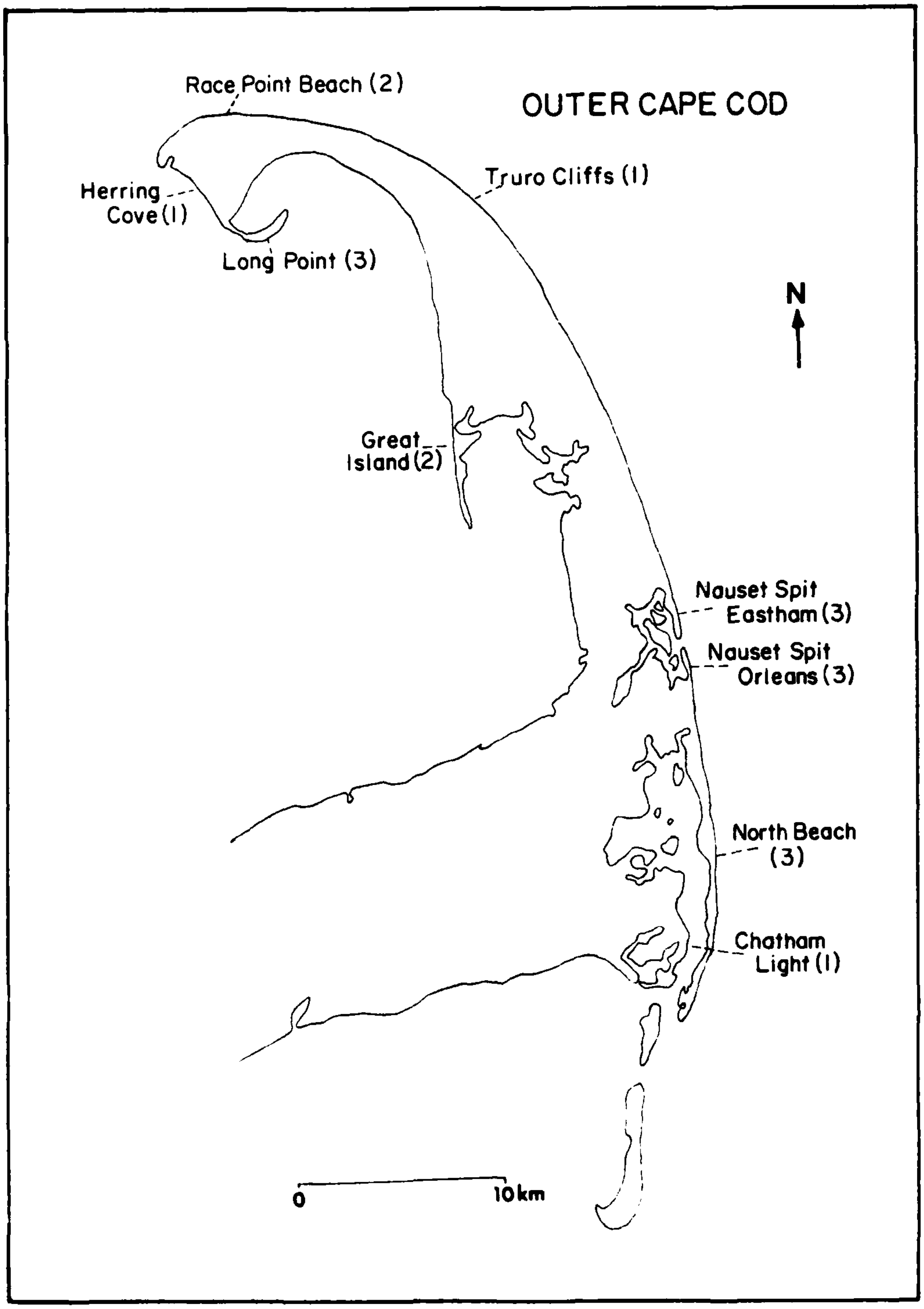


Figure 83. Location of 19 drift lines sampled on Cape Cod.

Table 33. Drift-line flora for 19 Cape Cod sites, 1978.

Species	F[1]	S[2]	Drift-line locations																			Pct appearance in 19 Cape Cod drift lines
			Nauset Spit-Eastham			North Beach (Orleans)			North Beach (Chatham)			Race Point Beach		Long Point			Great Island		Herring Cove	Chatham Light	Truro Cliffs	
			o[3]	st[4]	b[5]	o[3]	st[4]	b[5]	o[3]	st[4]	b[5]	o[3]	st[4]	o[3]	st[4]	b[5]	o[3]	b[5]	b[5]	st[4]	o[3]	
Agropyron pungens	x				x															x		11
Amaranthus hybridus		x										x										5
Ambrosia artemisiifolia		x								x												11
Ammophila breviligulata	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	100
		x	x	x	x		x	x		x	x	x				x				x		53
Arenaria peploides	x		x	x	x	x	x	x	x		x		x				x			x		58
Artemisia stelleriana	x		x	x	x	x	x	x	x	x	x	x	x	x			x		x	x	x	84
Atriplex arenaria		x		x	x			x			x	x		x		x	x		x	x	x	58
Atriplex patula		x		x	x			x		x	x	x		x		x	x				x	53
Bidens sp.		x								x		x							x			16
Brassica hirta		x						x			x									x		16
Brassica juncea		x						x														5
Cakile edentula		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	100
Carex silicea		x																			x	16
Chenopodium album		x									x							x		x		16
Convolvulus sepium		x			x			x				x		x			x			x		32
Cyperus polystachyos		x		x	x																x	?
Erechtites sp.		x						x		x	x			x		x		x		x		21
Euphorbia polygonifolia		x	x	x	x					x	x	x	x	x	x	x	x		x		x	68
Lactuca sp.		x								x												5
Lathyrus japonicus	x		x	x	x			x			x			x							x	37
		x	x	x	x	x	x	x		x	x	x			x				x	x		63
Lepidium virginicum		x								x						x				x		11
Oenothera biennis		x						x		x	x	x					x	x			x	37
Panicum virgatum		x		x	x																	11
Phytolacca americana		x									x											5
Raphanus raphanistrum		x						x														5
Rosa rugosa	x										x											5
Salsola kali		x	x	x	x	x		x	x	x	x	x		x		x	x		x	x	x	79
Solidago sempervirens	x			x	x			x			x				x						x	32
		x																		x		5
Spartina patens	x		x		x			x			x	x				x			x			37
Suaeda maritima		x									x			x		x		x				21
Teucrium canadense		x						x														5
Xanthium echinatum		x		x	x	x	x	x	x		x	x	x	x	x	x						89

[1]F = regenerated from fragments.

[2]S = seedlings.

[3]o = oceanic drift line.

[4]st = storm drift pile.

[5]b = bay drift line.

Table 34. Drift-line flora for nine Cape Cod sites, 1979.

Species	F[1]	S[2]	Drift lines: Coast Guard Beach o[3]	Coast Guard Beach b[4]	North Beach o[3]	North Beach b[4]	Long Point o[3]	Long Point b[4]	Herring Cove o[3]	Herring Cove b[4]	Race Pt. o[3]	Pct appearance in nine Cape Cod drift lines
Agropyron pungens	x			x	x	x						33
Ammophila breviligulata	x		x	x	x	x	x	x	x		x	89
		x	x	x	x	x						44
Arenaria peploides	x		x	x	x	x					x	56
Artemisia caudata		x		x		x					x	22
Artemisia stelleriana	x		x	x	x	x	x				x	67
		x		x								11
Atriplex arenaria		x		x	x	x		x				44
Atriplex patula		x	x	x	x	x	x	x	x	x	x	100
Brassica hirta		x				x					x	22
Brassica juncea		x				x					x	11
Cakile edentula		x	x	x	x	x	x	x	x	x	x	100
Carex silicea		x		x								11
Chenopodium albidum		x		x				x		x		33
Convolvulus sepium		x		x				x		x		33
Erectides sp.		x				x						11
Euphorbia polygonifolia		x		x		x	x	x		x	x	67
Helianthus sp.		x						x				11
Lathyrus japonicus	x		x	x		x	x		x	x		67
		x		x	x	x				x	x	56
Oenothera biennis		x		x	x	x						33
Panicum virgatum		x		x								11
Raphanus raphanistrum		x				x						11
Rhus radicans	x			x				x				22
		x		x								11
Rumex crispus		x			x	x						22
Salsola kali		x	x	x	x	x	x	x	x	x	x	100
Solanum dulcamara		x				x						11
Solidago sempervirens	x			x	x	x	x					44
		x		x								11
Spartina alterniflora		x		x								11
Spartina patens	x			x		x		x		x		44
		x		x								11
Suaeda maritima		x		x								11
Teucrium canadense		x				x						11
Xanthium echinatum		x	x	x	x	x	x		x	x	x	89

[1]F = regenerated from fragments.

[2]S = seedlings.

[3]o = oceanic drift line.

[4]b = bay drift line.

(2) Oceanic Drift Lines. A second type of drift accumulation present on Nauset Spit-Eastham was oceanic drift lines similar to those described by Chapman (1976; Fig. 84). Because Nauset Spit-Eastham is an eroding barrier, these drift lines are rare. On the southern end of the spit, however, large deposits of algae, *Ammophila breviligulata*, and salt-marsh grasses accumulated during the spring and early summer. One tide deposited debris which became buried by sand during the next tide and covered by more debris, creating a layered drift line as deep as 90 centimeters. Organic composition varies by location with algae, *Ascophyllum* sp. and *Fucus viscosum*, the most common elements in 1978. Samples of *Ascophyllum* collected from oceanic drift lines were dehydrated. Weight loss was 79 percent. Many seeds and a wide variety of plant fragments were present in these drift lines.

Figure 84. Oceanic drift lines.

Oceanic drift lines are densely vegetated by seedlings and regenerating fragments that can tolerate high levels of salt spray. These drift lines, high in nitrogen-rich algae and fine organic material, supported eight species of vascular plants on Nauset Spit-Eastham in 1978 (Table 29). A total of 20 species of vascular plants appeared in 7 oceanic drift lines sampled on Cape Cod in 1978 and 1979 (Tables 33 and 34).

(3) Bay Drift Lines. A third type of drift line found on Nauset Spit-Eastham, similar to the one described by Chapman (1976), was located along the dune and salt marsh interface and at the edges of washover features (Fig. 85). Composed largely of salt-marsh grasses (*Spartina patens* and *Spartina alterniflora*), these drift lines were, following the February storm, also rich in fine organic material torn from dunes and other eroded features. Organic material floating in the bay waters was deposited at the highest point reached by spring tides. In late March the first stable bay drift line was

Figure 85. Bay drift lines on Nauset Spit-Eastham.

established to the lee of the Nauset Spit-Eastham dune line. The deposits are water sorted with fine material carried farthest by the incoming tide. Individual bay drift deposits seldom exceed 10 centimeters in depth. Wind-deposited sand between spring tides results in burial of these mats of debris. In April 1978 additional drift material was laid over the lower edges of the drift line resulting in alternating layers of organic material and sand. Drift lines, initially about 50 centimeters wide, were occasionally expanded to several meters with additional spring tides and wind-transported sand.

Bay drift lines that were not adjacent to washovers were not buried between spring tides. Organic material that was not buried by sand was unstable and could be moved by winds and tides. Drift lines that were not buried by shallow aeolian sand deposits were not vegetated on Nauset Spit-Eastham.

Bay drift lines were widespread and densely vegetated in 1978. Many seedlings were present as well as many regenerating fragments; 22 species of flowering plants were present in Nauset Spit-Eastham bay drift lines (Table 29). Around Cape Cod, 34 species were located in 10 areas with bay drift lines in 1978 and 1979 (Tables 33 and 34).

(4) Comparison of Drift Lines. Not only did the species composition of the three types of drift lines vary, but plant size and mortality also differed. To determine the nature of these apparent differences, each of the three types of drift lines was excavated in June 1978 and plant measurements were taken. Examples of each type of drift line were chosen on Nauset Spit-Eastham outside study areas (Fig. 86). Particular attention was given to

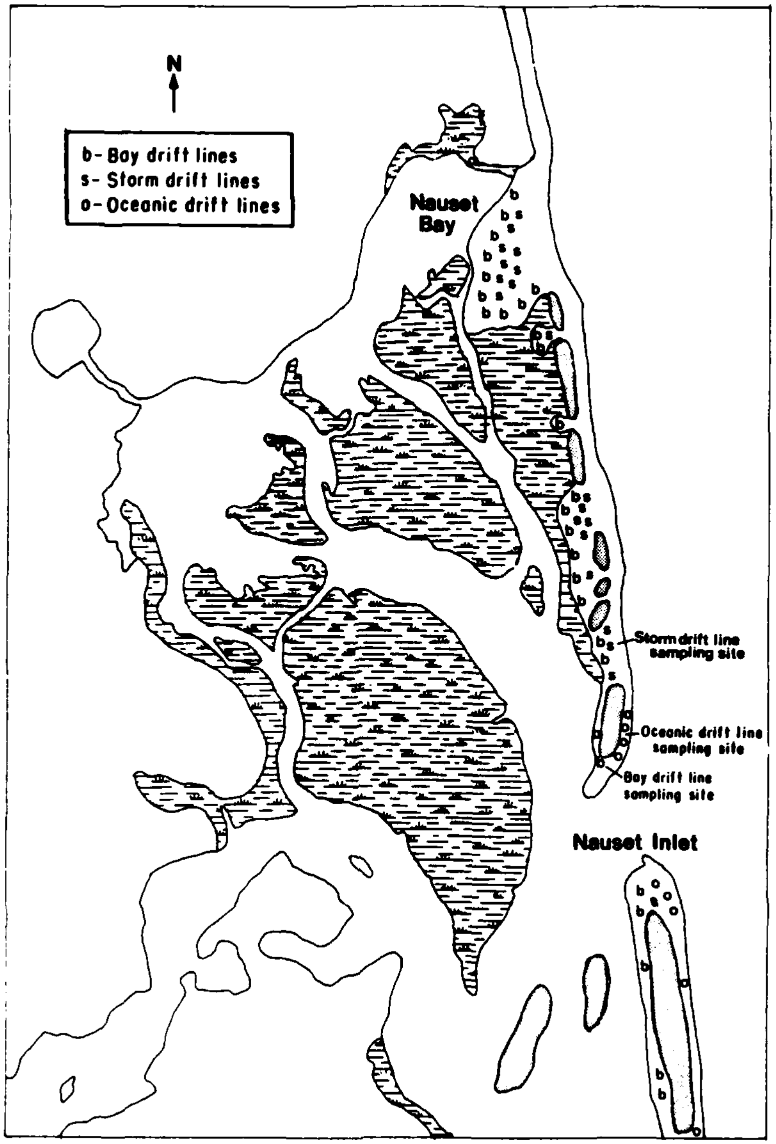


Figure 86. Location of Nauset Spit-Eastham drift lines.

regenerating *Ammophila breviligulata* fragments; 112 individual *Ammophila breviligulata* propagules were excavated in each of the three types of drift lines (Table 35). There are three types of *Ammophila breviligulata* fragments: tillers, rhizomes, and tillers with attached rhizomes. Each fragment was excavated and described. Only fragments with new growth were included.

In March 1978, 25 tillers of *Ammophila breviligulata*, collected at random from Nauset Spit-Eastham, were planted upright in sand and placed in the University of Massachusetts greenhouse. Within 3 weeks, 22 (88 percent) tillers showed new growth, while 3 (12 percent) did not grow. Of the 321 *Ammophila breviligulata* plants excavated (15 individuals were seedlings), 226 (70 percent) consisted of at least one tiller, 234 (73 percent) consisted of at least one rhizome, and 148 (46 percent) were made up of both tiller and rhizome (Table 35). Tiller length averaged 18.4 centimeters with a range from

Table 35. Measurements of *Ammophila breviligulata* in drift lines, June 1978.

Fragments	Oceanic drift line				Storm drift line				Bay drift line				Totals		
	No.	$\bar{X}$	s.d.	Range	No.	$\bar{X}$	s.d.	Range	No.	$\bar{X}$	s.d.	Range	No.	$\bar{X}$	Range
No. of fragments sampled	107				108				106				321		
No. of seedlings	5				4				6				15		
Fragments (pct) made up of tiller parts		10.6				27.1				36.8				24.8	
Fragments (pct) made up of rhizome parts		25.2				18.7				38.8				27.5	
Fragments (pct) made up of tillers and rhizomes		62.6				52.8				22.6				46.1	
Tiller part length (cm)	85	20.0		6.5-30	99	18.5		4-41.5	64	15.9		6-29	248	18.4	4-41.5
Rhizome part length (cm)	92	20.8		0.5-114	79	18.0		0.5-137	65	23.2		1-90	236	20.5	0.5-137
Burial depth (cm) of fragment		16.5	6.7	5.5-34		9.8	5.2	3-32		8.4	2.70	3-16		11.6	3-34
New tillers developing from the continuation of former tiller apex (pct of all fragments)		11.2				23.2				17.0				17.1	
New tillers developing from lateral buds (pct of all fragments)		83.2				84.3				84.0				83.8	
Tillers per fragment		2.3	1.5			2.0	1.9			1.3	0.71			1.9	
Leaves per fragment		6.6	4.1			4.7	5.4			2.5	1.60			4.7	
Length (cm) of longest leaf per new tiller		34.8	10.0			27.0	13.5			22.9	9.50				
New rhizomes per fragment	0				0				0				0		

4 to 41.5 centimeters. Rhizome length averaged 20.5 centimeters with a wide range from 0.5 to 137 centimeters. There were no statistically significant differences between oceanic and storm drift lines with respect to propagule type. Bay drift lines, however, had propagules that were smaller than either oceanic or storm drift lines. Bay drift material apparently is more fragmented before deposition than material deposited elsewhere.

For each fragment the point of initiation of new growth was located and recorded as the burial depth. Mean depth was 11.6 centimeters for all sites, with a range from 3 centimeters in the bay and storm drift lines to as much as 34 centimeters in oceanic drift lines. Excavations in other areas indicated that fragments buried by 1 meter of sand can remain alive and begin to grow. Fragments buried at 90 centimeters in April 1979 recovered and grew to the sand surface within 5 weeks.

Mean fragment depth was 8.4 centimeters in bay drift lines, 9.8 centimeters in storm drift lines, and 16.5 centimeters in oceanic drift lines. Bay and storm drift-line burial depth means did not differ significantly ($P > 0.05$), but both did differ from oceanic drift lines ($P < 0.01$). Recovery of fragments from lower burial depths in oceanic drift lines reflects the overall morphology of these features and not differential survival of propagules at varying depths. Successive deposition of drift material on the ocean beach caused fragments to be buried much deeper than in other areas.

New tillers may originate from a continuation of a previously growing shoot or from buds located along rhizomes. Seventeen percent of the Nauset Spit-Eastham fragments had tillers that recommenced growth; 84 percent had lateral buds that broke dormancy.

The number of new tillers supported by a fragment is a measure of either reallocatable reserves of that fragment or environmental conditions within the habitat. Fragments were excavated in June, and the number of new tillers, including axes that had not yet broken the sand surface, was recorded (Table 35). Statistical analysis showed that the number of axes present on oceanic and storm drift-line fragments is not significantly different ($P > 0.05$). Bay drift-line fragments, however, supported significantly ($P < 0.05$) fewer tillers than either of the other types of fragments. Bay drift-line fragments were significantly smaller than others, which may indicate that reallocatable resources were less available.

In August 1978 fragments at the same sites were again excavated and tiller numbers were counted. In the oceanic and storm drift lines, mean tiller number declined (Table 36), probably because some tillers that originated near the sand surface died during the late July to early August drought. The number of bay drift-line tillers per fragment increased. The mean tiller number at all three sites did not differ significantly in August. Smaller fragment size (and therefore lower reserves) found in bay drift lines did not seem to be important in the ultimate number of tillers produced, since once a tiller reaches the sand surface, photosynthesis provides the major source of carbohydrates needed for growth.

Table 36. Measurements of *Ammophila breviligulata* in drift lines, August 1978.

Fragments	Oceanic drift line		Storm drift line		Bay drift line		Totals
	$\overline{X}$	s.d.	$\overline{X}$	s.d.	$\overline{X}$	s.d.	$\overline{X}$
Tillers per fragment	2.1	1.1	1.8	1.0	1.8	1.1	1.9
Leaves per fragment	7.2	4.0	6.6	4.3	6.0	4.1	6.6
Length (cm) of longest leaf per new tiller	58.6	8.0	36.4	11.2	49.8	10.5	48.2
New rhizomes per fragment	0.8	0.9	0.5	0.9	0.3	0.5	0.5
Length (cm) of new rhizomes per fragment	32.4	31.1	5.6	5.1	5.8	4.3	19.0

The number of leaves on each regenerating fragment and on each tiller early in the growing season is also a measure of reallocatable resources and habitat conditions. Once again bay drift lines had less vegetative growth in early June than either oceanic or storm drift lines (Table 35). Highly significantly fewer leaves were produced per fragment and per tiller than in either the oceanic or storm drift lines, which did not differ significantly.

In August the number of leaves per fragment was again counted (Table 36). Fewer leaves were found on fragments in bay drift lines than in the oceanic drift line ($P < 0.01$). Bay drift lines did not differ from storm drift piles; storm and oceanic drift habitats did not differ with respect to leaf number per fragment. While tiller numbers in bay drift lines increased during the growing season, the number of leaves (and likely the amount of photosynthate) was still less than in oceanic drift lines.

Apparently, smaller propagule size in bay drift lines leads to slow initial growth, which by August is compensated for by habitat conditions. Storm drift piles have larger fragments and better initial growth but may die during the hot, dry summer months. Plants in oceanic drift lines appear to grow well initially and to continue to do better than those in other areas.

Perhaps the best estimation of the value of a particular drift line in the recolonization of washovers is the ability of established *Ammophila breviligulata* fragments to expand laterally. Horizontal rhizomes were not present on any *Ammophila breviligulata* fragments excavated in June, but were common on fragments excavated in August (40 rhizomes greater than 1 centimeter long on 75 plant fragments; Table 36). Lateral rhizome production was the greatest in oceanic drift lines and the least in bay drift lines. There was a significant difference ($P < 0.05$) in rhizome number per fragment between bay and oceanic drift lines. Rhizome length was clearly greater in oceanic drift lines ($P < 0.01$) than the other two habitats. Other plants measured in the three drift lines indicated that the ocean site generally produced larger plants. Storm drift-line plants were generally smallest.

The type of organic material found in a drift line undoubtedly accounts, in part, for the growth response of colonizing species. Algae, one of the principal components of oceanic drift lines, generally has a relatively high carbon-nitrogen ratio (around 15:1) and may supply plants with usable nitrogen, which is usually the limiting factor in coastal environments. Algal cells, which are much more absorbent than higher plant cells due to a lack of lignin, are also able to retain large amounts of moisture, which is available to colonizing species.

On the other hand, *Ammophila breviligulata*, the principal component of storm drift piles, has a high carbon-nitrogen ratio (greater than 75:1) and may supply less nitrogen to colonizing plants. *Ammophila breviligulata* rhizomes are extremely wiry with high concentrations of lignin, and aggregates of this species are very poor in moisture retention. The general nutrient status of bay drift material is unknown, but because of its texture it appears at least to retain greater amounts of moisture than storm drift piles.

To determine the growth response of *Ammophila breviligulata* to different types of drift material, an experiment was designed in which fragments, planted with different types of organic material, were measured throughout the growing season. A wooden frame was constructed on a washover fan with four 1- by 1.5-meter compartments. Each compartment was excavated to a depth of 20 centimeters. Twenty-five genetically identical *Ammophila breviligulata* fragments were placed horizontally on the surface. Three compartments were covered with 15 centimeters of drift material (*Ascophyllum*-algae, *Ammophila breviligulata* debris, or bay drift material), and one was filled with sand. Each treatment was covered with approximately 5 centimeters of sand.

Ammophila breviligulata is known to grow best in areas of sand accumulation. A fifth treatment was established in which a metal barrel with its bottom removed was placed over 38 tillers in an accreting area and filled with sand. Measurements were made of *Ammophila breviligulata* tillers that grew through 90 centimeters of sand.

The tiller number per treatment, the mean leaf length per tiller, and the length of the longest leaf of each tiller were recorded between 12 June and 27 August 1978 (Tables 37, 38, and 39).

Initially, the greatest number of tillers were produced in the *Ammophila breviligulata* debris treatment, reflecting the presence of additional fragments among the drift material itself (Figs. 82, and 87; Table 37). After early July, however, the algal and 90-centimeter burial treatments produced greater numbers of axes per treatment. Throughout the summer, the treatment without drift consistently produced fewest axes. The mean longest leaf for each tiller was calculated for each treatment (Table 38; Fig. 88). Again, the algal and 90-centimeter burial treatments produced the best growth. Although the mean longest leaf lengths for these two treatments were not significantly different ($P > 0.05$), they both differed from all other treatments ($P < 0.01$). Treatments with bay drift material or sand did not differ significantly from one another ($P > 0.05$).

Finally, the range of longest leaf length per tiller for each treatment was also recorded to take into account the fact that healthy treatments are continually producing new axes, which initially decreases mean leaf length

Table 37. Number of *Ammophila breviligulata* tillers per treatment, 1979.

Date	Bay drift	Algae	*Ammophila breviligulata* fragments	Sand	90 cm of burial sand
25 Mar.	19	18	43	8	15
6 June	24	22	46	12	---[1]
12 June	27	33	46	12	---
19 June	28	34	56	13	---
25 June	31	51	57	14	42
3 July	35	66	57	15	66
10 July	40	90	57	19	98
19 July	--	--	--	--	119
25 July	48	136	66	28	121
1 Aug.	60	129	57	33	127
8 Aug.	70	153	75	37	133
14 Aug.	64	145	88	50	133
27 Aug.	88	151	93	63	137

[1] Not sampled.

Table 38. Mean and maximum number of leaves per tiller for each treatment, 1979.

Date	Bay drift		Algae		*Ammophila breviligulata* fragments		Sand		90 cm of burial sand	
	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)
12 June	2.5	4	2.6	4	2.5	5	2.4	3	--	--
19 June	3.3	5	3.7	5	3.2	5	3.3	5	--	--
25 June	3.3	4	3.5	5	3.1	5	3.2	5	3.4	6
3 July	3.2	5	3.4	6	3.2	5	3.5	5	3.4	8
10 July	3.6	5	3.9	6	3.3	5	3.6	5	3.2	7
19 July	--	--	--	--	--	--	--		4.0	7
25 July	3.8	5	4.1	8	4.0	6	4.2	7	4.0	7
1 Aug.	3.6	6	4.1	7	4.0	7	4.1	7	4.0	7
8 Aug.	3.8	6	4.4	8	4.1	7	4.4	8	3.8	6
14 Aug.	4.7	9	4.7	9	4.2	9	4.6	8	4.5	8
27 Aug.	3.9	7	5.1	10	4.2	8	4.1	7	4.2	7

Table 39. Mean and maximum longest leaf lengths per tiller for each treatment, 1979.

Date	Bay drift		Algae		*Ammophila breviligulata*		Sand		90 cm of burial sand	
	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)	Mean (cm)	Max. (cm)
12 June	31.9	46.0	33.6	51.0	24.4	52.0	29.9	42.5	----	----
19 June	34.1	48.0	37.9	61.0	24.1	51.0	33.0	44.0	----	----
25 June	34.8	52.5	37.8	53.5	26.5	52.0	35.0	48.5	38.2	63.5
3 July	37.6	55.5	44.5	67.0	31.2	53.0	39.7	56.0	40.9	73.0
10 July	39.7	58.0	47.8	92.0	35.8	59.0	40.0	61.5	48.1	88.0
19 July	----	----	----	----	----	----	----	----	56.6	100.0
25 July	43.5	70.0	54.4	102.0	46.5	70.5	47.5	76.0	65.0	116.0
1 Aug.	49.1	80.0	67.6	114.0	48.9	87.0	55.8	87.0	75.1	116.0
8 Aug.	50.0	82.5	70.8	117.0	49.5	84.0	55.3	96.0	82.1	122.5
14 Aug.	57.6	92.0	75.9	123.0	52.8	88.5	54.0	98.0	86.5	123.5
27 Aug.	60.9	100.0	83.8	131.5	58.5	93.0	61.0	106.5	94.3	132.0

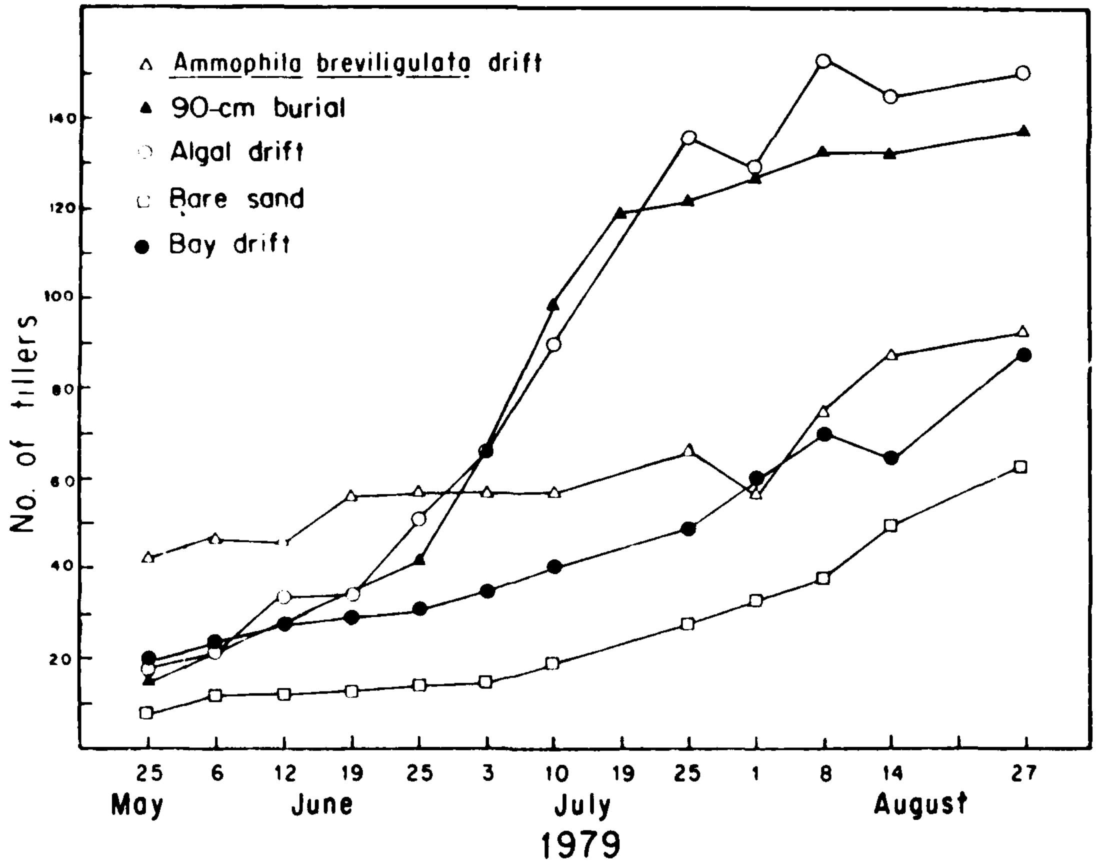


Figure 87. Comparison of change in tiller number of *Ammophila breviligulata* in five habitats.

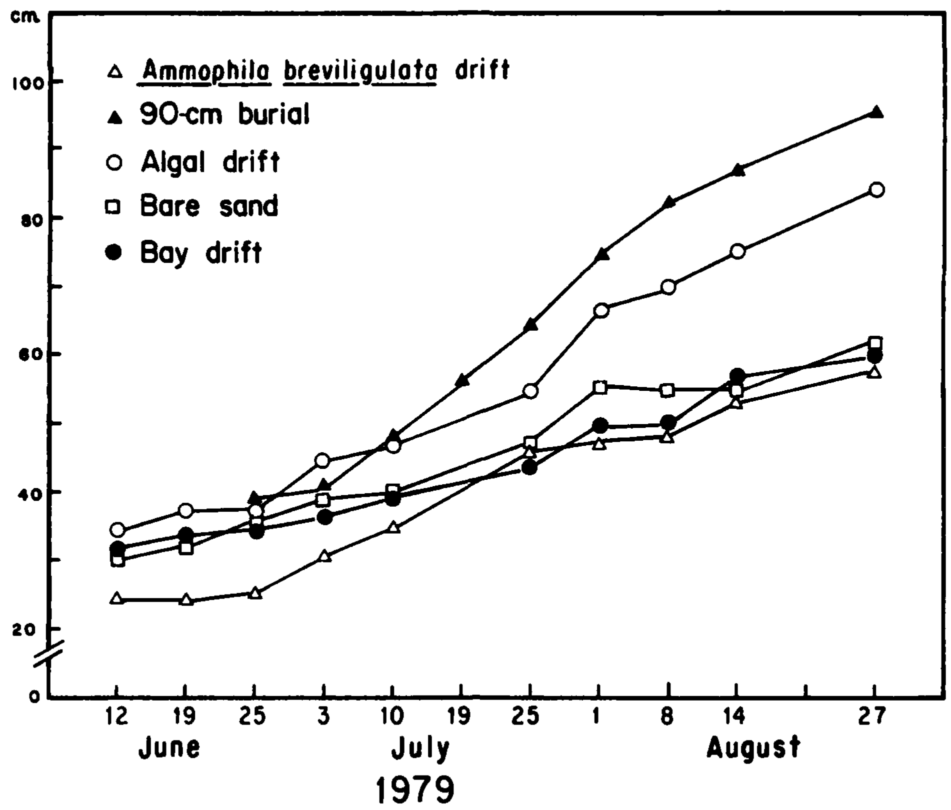


Figure 88. Comparison in mean leaf length of *Ammophila breviligulata* per tiller in five habitats.

(Table 39; Fig. 89). Once again the algal and 90-centimeter burial treatments were similar to each other and greater than all other treatments. Although measurements were not taken, chlorophyll content of the algal and 90-centimeter burial treatments also appeared to be far greater than all other treatments.

The presence of algal drift material enhances *Ammophila breviligulata* growth similar to that of accreting areas. Algae undoubtedly provides both increased moisture availability and nitrogen, which lead to optimal plant growth. Oceanic drift lines, rich in algal components, are by far the best habitats on Nauset Spit-Eastham for plant colonization. Below-ground production (rhizomes), which leads to vegetative expansion, is greatest in oceanic drift lines.

Oceanic drift lines, while effective sites of plant colonization, have not played an important role in the recolonization of washovers on Nauset Spit-Eastham because the area is continually eroding. Vigorous growth of oceanic drift-line vegetation was found in 1978 and 1979 along Nauset Spit-Eastham, but did not survive winter storms. At best, these sites provide new propagules for resettlement in other areas.

Bay drift lines have the densest vegetation and most varied flora of all Cape Cod drift lines, although they do not have the luxuriant plant growth of either oceanic drift lines or accreting areas. During the 2 years after the

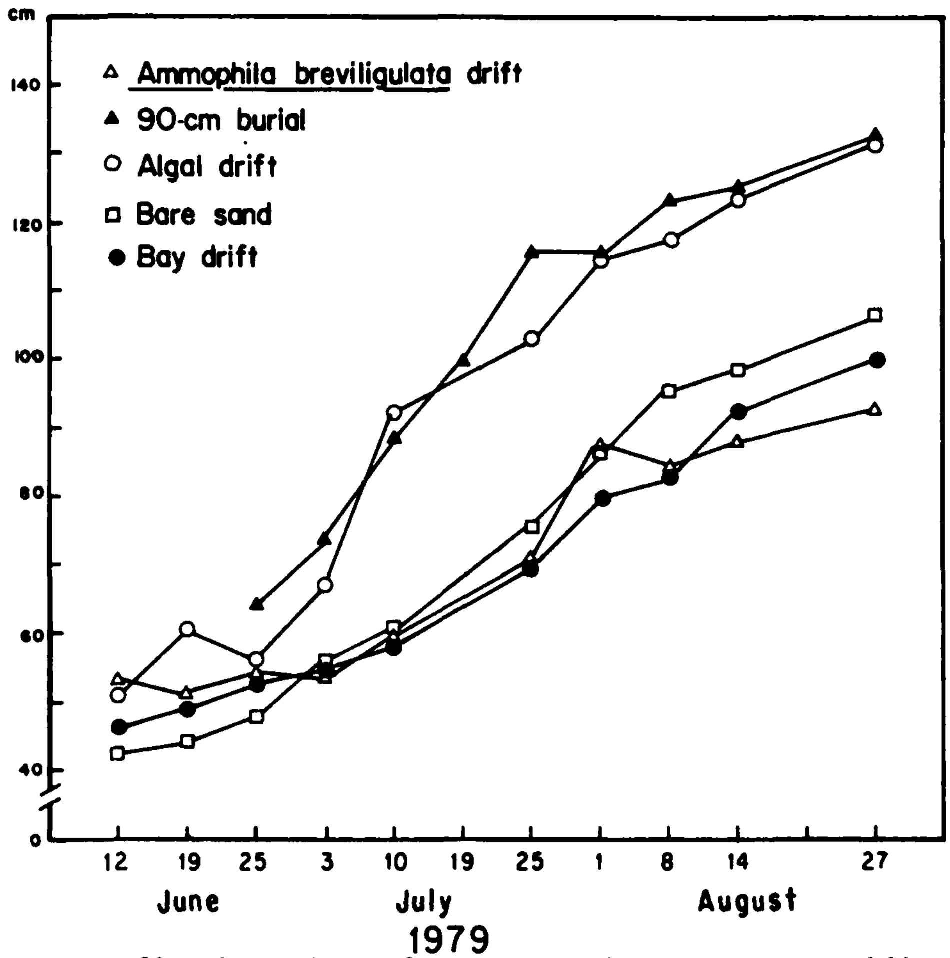


Figure 89. Comparison of maximum leaf length of *Ammophila breviligulata* in five habitats.

February 1978 storm, many bay drift lines established in March 1978 persisted, although many other areas on Nauset Spit-Eastham were destroyed by storms. New drift material was continually added at lower elevations to long-standing drift lines and subsequently buried by windblown sand. This additional material acted as a buffer against storm activity, which occasionally eroded the outer edges of the drift line, leaving the initial core intact.

The bay drift lines are also buffered in terms of vegetative composition. Dune vegetation is killed by saltwater inundation during the early part of the growing season. Salt-marsh vegetation is killed by either high levels of burial or by continual low levels of burial. Because both dune and salt-marsh vegetation are present in bay drift lines, either plant community, depending on elevation, can become established from drift-line plants. *Ammophila breviligulata*, commonly found in bay drift lines, can, with sufficient sand supply, begin to build dunes. *Spartina patens*, also found in this habitat, will eventually be outcompeted by *Ammophila breviligulata* which thrives with burial. Without necessary dune-building sediment or with higher than normal spring tides during the growing season, *Ammophila breviligulata* is killed, while *Spartina patens* flourishes. Bay drift lines can thus become either the site of new salt marshes or dunes. The bay drift lines were the most common features on Nauset Spit-Eastham washover fans.

Storm drift piles were richest in *Ammophila breviligulata* propagules and were widely distributed on Nauset Spit-Eastham in 1978. Large numbers of *Ammophila breviligulata* tillers appeared in these piles early in the growing season. Deflation of open washovers made these debris piles appear as newly developing dunes. In 1978 some of the *Ammophila breviligulata* fragments that regenerated in storm drift piles did not, however, survive the hot, dry summer months. Rhizome development and aboveground plant growth were poorer than in oceanic drift lines.

Like bay drift lines, storm drift piles were less susceptible to storm erosion than oceanic drift lines. Many of these piles developed around large tangles of shrubs or remnants of destroyed cottages. Again spring tide drift was deposited at lower elevations around these features and provided protection from erosion. While storm drift piles were poor in species diversity and plant survival, they outlasted oceanic drift lines and helped to initiate dune building.

IV. BARRIER EVOLUTION

1. Introduction.

The evolution of Nauset Spit was determined from geologic core data, historical charts and maps, sequential vertical photos, and detailed field analysis of 15 areas on the spit. Stratigraphic profiles were constructed from core data so that the third dimension of the barrier landform could be analyzed to determine the role of principal processes in landward migration and to establish a time frame for barrier rollover. Historic changes were determined by an examination of old charts and maps dated as far back as the early 1600's for Nauset Spit. These early charts provide a useful description of the barrier, which can be used to corroborate and expand core information. Data from early maps and charts, however, can only be used for qualitative assessments, because early mapmaking was often subjective and inaccurate. U.S. Coast and Geodetic Survey charts dating from 1851, made from controlled field measurements, were used for quantitative analyses of recent trends. Finally, detailed field analysis of areas with an established history yielded information concerning rates and means of development of existing barrier features. A complete picture of the evolution of Nauset Spit was assembled from these four types of data.

2. Geologic Trends.

a. Methodology. A series of cores were taken along transects at Nauset Spit-Eastham washover site 1 (Fig. 13) and on North Beach (Fig. 90). The relative elevation of each core was determined by transit and rod surveys for cross-sectional analysis. Since permanent bench marks were not available, elevations were established in relation to an estimation of mean water level (MWL) on the beach foreshore.

Coring was conducted by the pile-driving technique, which can be accomplished by a few individuals in marsh or fine sandy substrates. At Nauset Spit, however, the sediment is coarse sand (mean of 0.45 millimeter) which made the coring very difficult and required additional manpower.

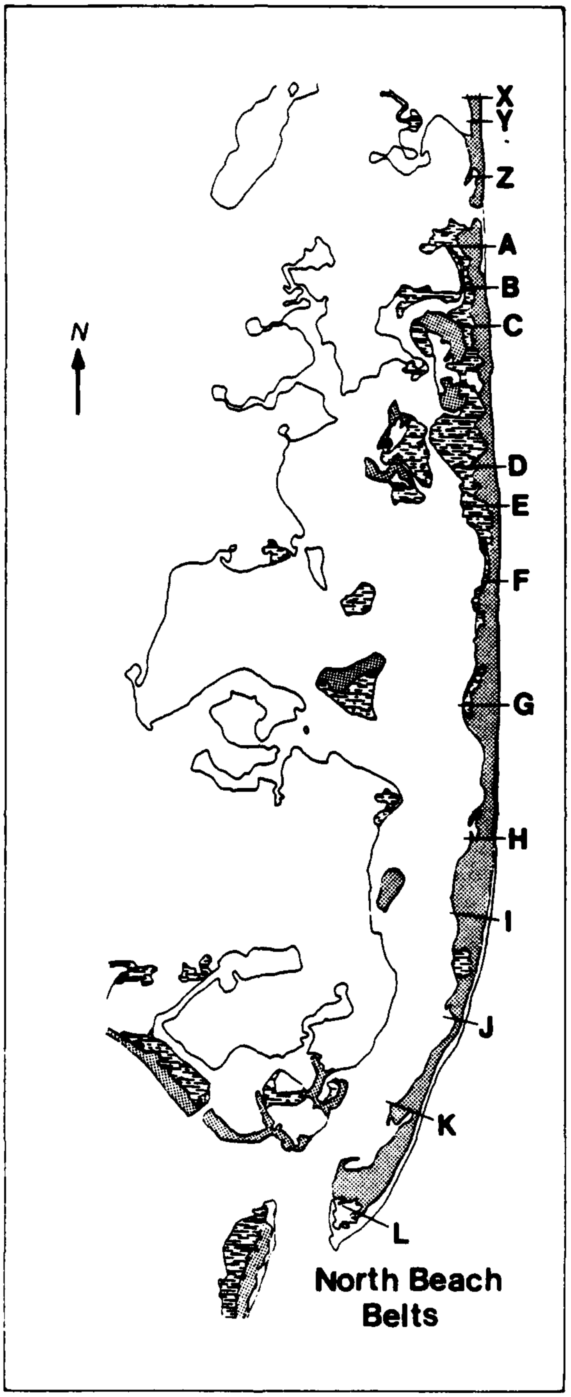


Figure 90. Locations of the 15 belts on North Beach.

A 5-meter-high tripod was initially set up over the coring site. A 20-kilogram weight, raised by a rope and pulley system suspended from the tripod, was used to drive the corer, a piece of polyvinyl chloride (PVC) pipe, 7 centimeters in diameter and 3 meters long, into the ground. After the PVC pipe was pounded into the ground, a measurement was made from the top of the core to the substrate surface to account for compaction. Water was then poured into the rest of the pipe and an airtight plumber's plug was used in the end to prevent the core from slipping out during extraction. Two 5-ton-capacity truck jacks were hooked under a 7-centimeter metal collar that was tightened around the outer perimeter of the coring pipe. The PVC pipe with the enclosed core was then removed from the ground.

The cores were taken to the laboratory for analysis. Core tubes were split into lengthwise halves by a table saw. A piano wire was pulled along the vertical length of the core to separate sandy layers, and a knife was used to cut salt-marsh peat. The core was split into sediment samples based on textural and mineralogical differences. The type of peat material (high or low marsh) was identified with a binocular microscope (Neiring and Warren, 1977), and organic materials were saved for radiocarbon dating.

b. Analysis of Data. Correlation of a series of cores as a stratigraphic section illustrates the long-term, landward migration of the spit. Figure 91 is a cross section constructed from cores taken at site 1 on Nauset Spit-Eastham. Core C-1 was taken in the middle of a narrow washover throat in the dune line, and two cores (C-2 and C-3) were taken in the recently overwashed salt marsh. An outcrop of peat (*Spartina alterniflora*) was present on the beach during the survey period (Fig. 92). A second peat layer 60 centimeters thick, dated at 815 years B.P. ± 95 years (University of Miami) and typed as *Spartina patens* with lenses of *Spartina alterniflora*, was found at the bottom of a core C-1, more than 4 meters below the present surface. Above this organic layer was an orange-white sandy section, characterized by coarse sandy zones and heavy mineral laminations. This material was subaerially deposited by overwash with evidence of some aeolian layers. The surface layers in cores C-1 and C-2 were recent washover deposits from the 1972 northeaster (Fig. 91).

From these cores it was evident that a well-developed salt marsh existed behind the barrier dune on Nauset Spit-Eastham as early as 815 years B.P. Washover deposits buried the salt marsh sometime after this time, and dunes subsequently formed in this location. The presence of peat also indicated that an inlet had not existed in this area within the past 800 years and the dunes must have formed on top of the washovers.

A more detailed transect of cores was obtained from North Beach, which clearly shows the mechanism of the barrier retreat (Fig. 93). The coring transect was again established through a recent washover throat to take advantage of the low elevation surface in the dune field. One core was taken in the back dune, and one was taken in the barrier grasslands. The salt-marsh sediments were overlain by horizontally stratified washover deposits along the entire coring transect. The marsh sediments of core NBI-2 were dated by radiocarbon methods at 360 years B.P. ± 125 years (Geochron Laboratories) at the base and less than 200 years B.P. (USGS) at the top. These dates indicate a rapid rate of retreat for North Beach. Less than 300 to 400 years ago, a salt marsh existed behind the barrier at this location on North Beach. Salt marsh, which persisted for a few hundred years, was eventually killed by

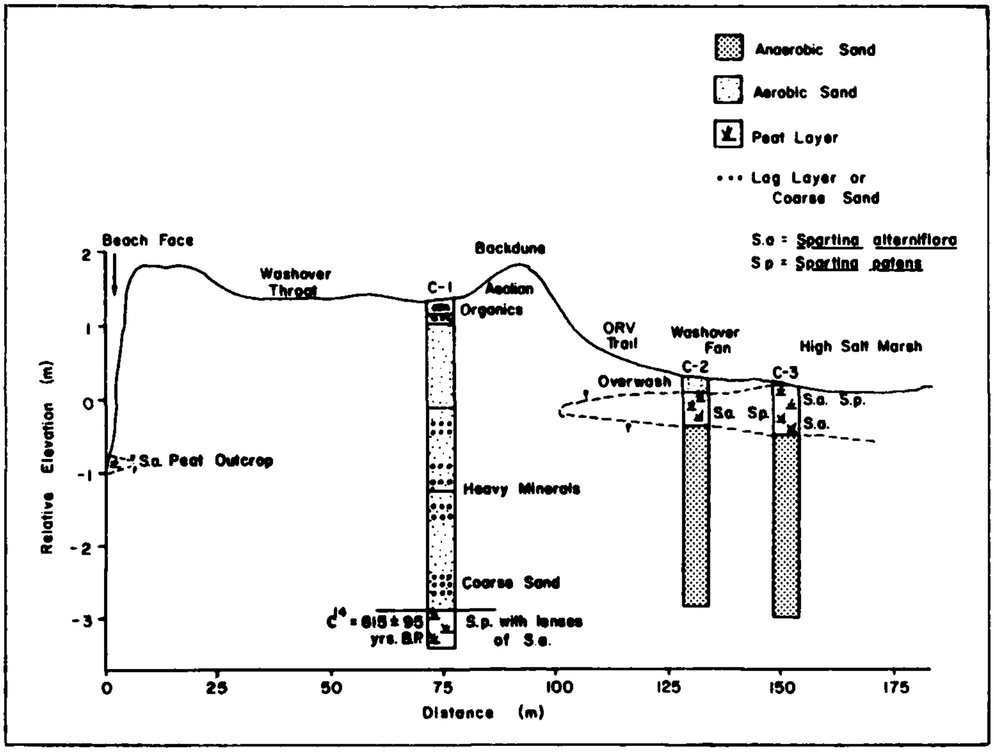


Figure 91. Stratigraphic cross section based on core analysis, site 1 (Nauset Spit-Eastham).

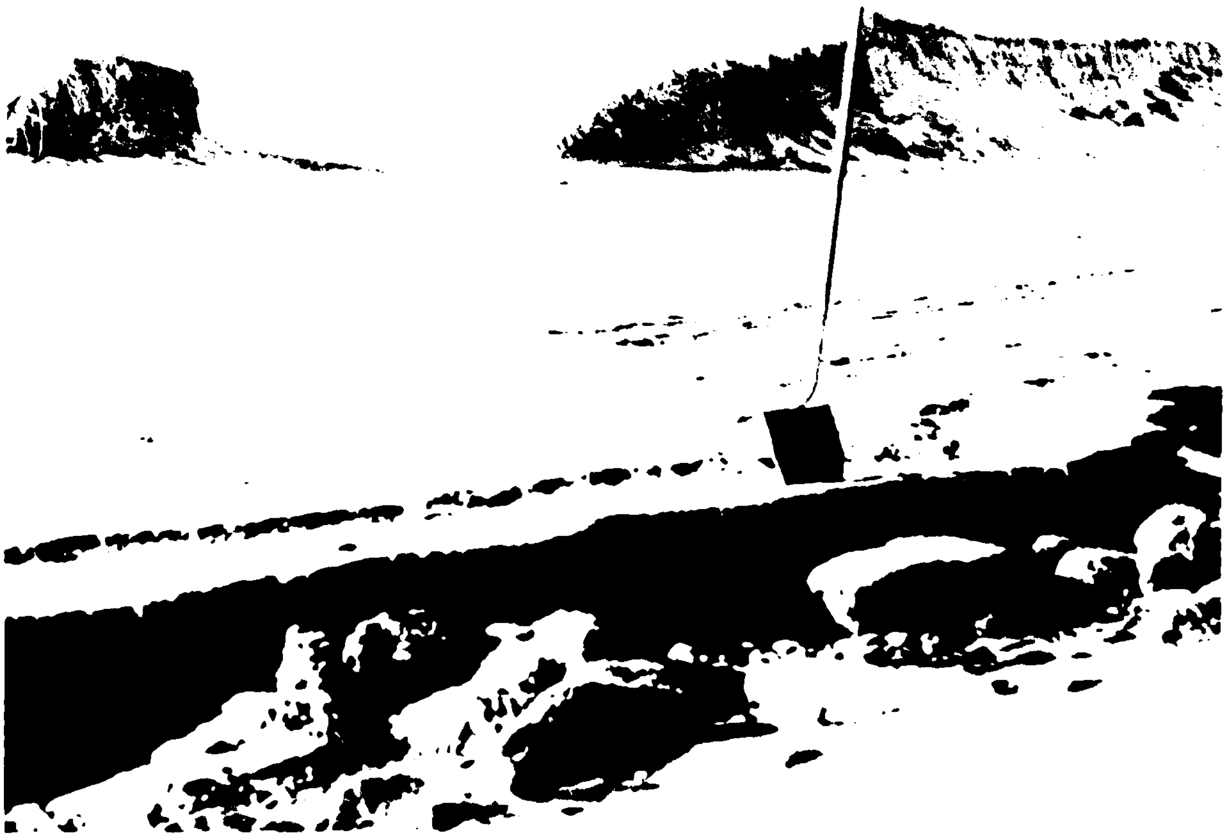


Figure 92. Exposure of salt-marsh peat on beach foreshore, 1976.

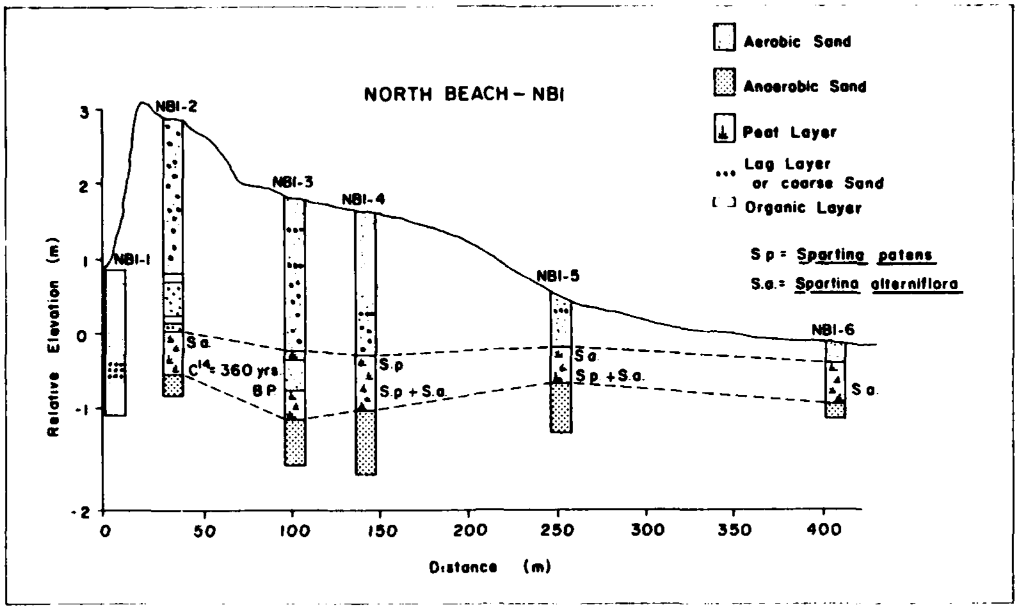


Figure 93. Stratigraphic cross section at Old North Beach, showing overwash sand above salt-marsh sediments.

overwash burial. In less than 200 years, dunes formed on the old washover, and the oceanic shoreline retreated landward so that salt-marsh peat was near the ocean beach. Therefore, the dune line was displaced landward by at least its former width in less than 200 years. The presence of a preserved peat layer indicated that recent landward migration on North Beach at this location was preceded by overwash processes with upward sediment accretion on the salt-marsh surface.

3. Historic Changes: Qualitative.

a. Introduction. Maps, charts, and written descriptions of Nauset Spit (1602 to 1868) were consulted to determine the historic evolution of the barrier system. The older maps and charts were compiled primarily by early French and English explorers interested in nearshore navigation and anchorage and sites for new settlements. Many of these charts did not take into consideration features such as dunes, salt marshes, or washovers. Even when physiographic features were clearly noted, quantitative measurements were not possible because the map-making quality was inconsistent and accuracy varied greatly. Early maps did, however, often indicate the general location of important features such as inlets, dunes, salt marshes, and glacial remains, which could be used to substantiate other research findings.

Much of this information has been summarized by other investigators working in the Nauset Spit system (Mitchell, 1871, 1875; Johnson, 1925; Nickerson, 1931; Goldsmith, 1972; Giese, 1978; Onysko, 1978; McClennen, 1979; U.S. Army Engineer Division, New England, 1979; Wright and Brenninkmeyer, 1979). These accounts were synthesized and new information was added to develop a complete picture of the evolution of the Nauset Spit system since 1602.

b. <u>Nauset Spit-Eastham</u>. The earliest reliable source of information on Nauset Spit is a map and written account by Samuel de Champlain in 1605. This map, along with other early accounts by Gosnold (1602), Hudson (1609), and Bradford (1622), is included in a shoreline diagram by Nickerson (1931; Fig. 94), who attempted to reconstruct the Cape Cod shoreline observed by the Mayflower Pilgrims in 1620. Of particular interest on this composite map is the configuration of the Nauset Harbor-Point Care area. In the past 350 years, there have been major adjustments of the Nauset Spit shoreline. A comparison of Champlain's 1605 map (Fig. 95) and a 1964 USGS quadrangle map indicates the nature and magnitude of these changes (Fig. 96). In 1605 Nauset Harbor was protected by two barrier spits separated by Nauset Inlet. Between 1605 and 1978, the south spit moved landward approximately 0.8 kilometer at a rate of 2.1 meters per year (Wright and Brenninkmeyer, 1979). This is considerably faster than the rate of shoreline recession in the area today (0.9 meter per year, Marindin, 1889; 1.5 meters per year, Zeigler, 1960; and 0.9 meter per year, this study).

An inspection of Champlain's 1605 map, interpreted by Ganong (1922), gives some insight into the rapid landward migration of the south spit (Fig. 95). There is a notation accompanying the map that indicates there was "a nucleus of upland, doubtless one of the little drumlins so plentiful on this coast" with a grove of trees, which is characteristic of glacial features. The southern spit of Nauset Harbor in 1605 was a tombolo (a spit connecting an island to the mainland). This small glacial section had eroded at a slower rate than the rest of the shoreline for many years. When the glacial deposit was finally eroded by the sea prior to 1833 (Nickerson, 1931), the shoreline rapidly retreated to an equilibrium position, resulting in a straightening of the shoreline. Then the northern spit must have also eroded rapidly at its southern end, since it would have projected seaward with the loss of the south spit drumlin.

Champlain's 1605 map indicates that much of the surface of Nauset Harbor was covered with mudflats. Salt marsh was confined to the northeast corner of the embayment immediately behind the barrier dunes. To determine the depth and age of the present salt marsh, indicated as mudflats on Champlain's map, two shallow cores were taken, using the piledriver technique. In one core taken near the center of Nauset Marsh, salt-marsh peat was found in the upper 80 centimeters of the column. The lowest organic layer was radiocarbon dated at 1485 years B.P. ± 125 years (University of Miami). In the second core, taken near the southern end of Nauset Marsh, salt-marsh peat was found in the top 1 meter of sediment, and a radiocarbon date of the basal peat was fixed at 750 years B.P. ± 85 years (Beta Analytic). Clearly, Champlain must have seen salt marsh in the center of Nauset Harbor in 1605. Champlain, a noted geographer, was primarily interested in the Nauset Harbor area as a settlement site with good anchorage. To a sailor, mudflats and salt marsh were equally unnavigable.

Although the spit has migrated a considerable distance landward, the Nauset Harbor area on Champlain's map of 1605 appears quite similar to its configuration in 1977 (Fig. 2). Two barrier spits with well-developed dunes protected a large salt marsh with poorly navigable channels. The only major difference between the maps was the drumlin in 1605 that altered the smooth contour of the outer shoreline.

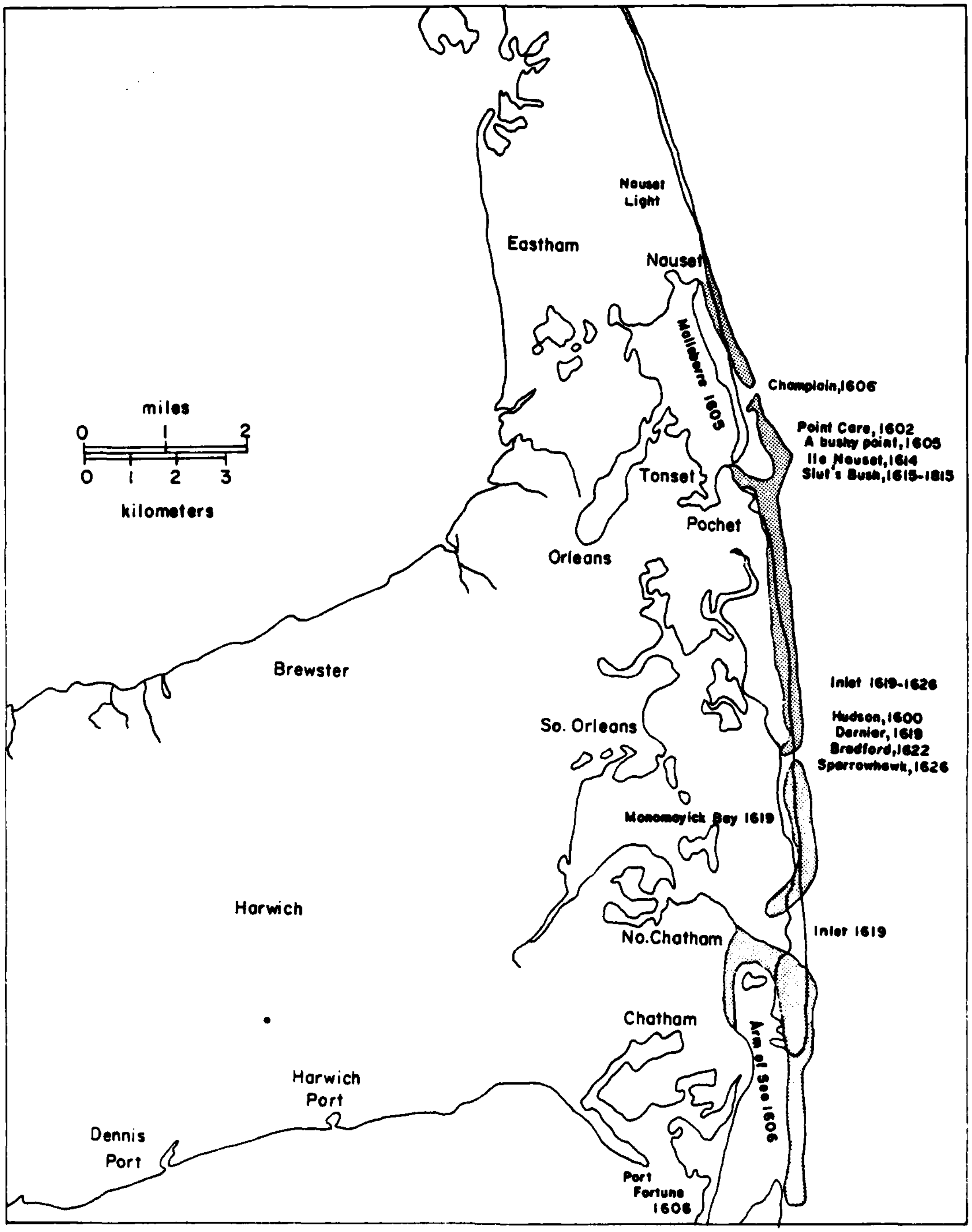


Figure 94. Shoreline diagram by Nickerson (1931), after Goldsmith (1972).

Figure 95. Champlain's 1605 map of Nauset Harbor.

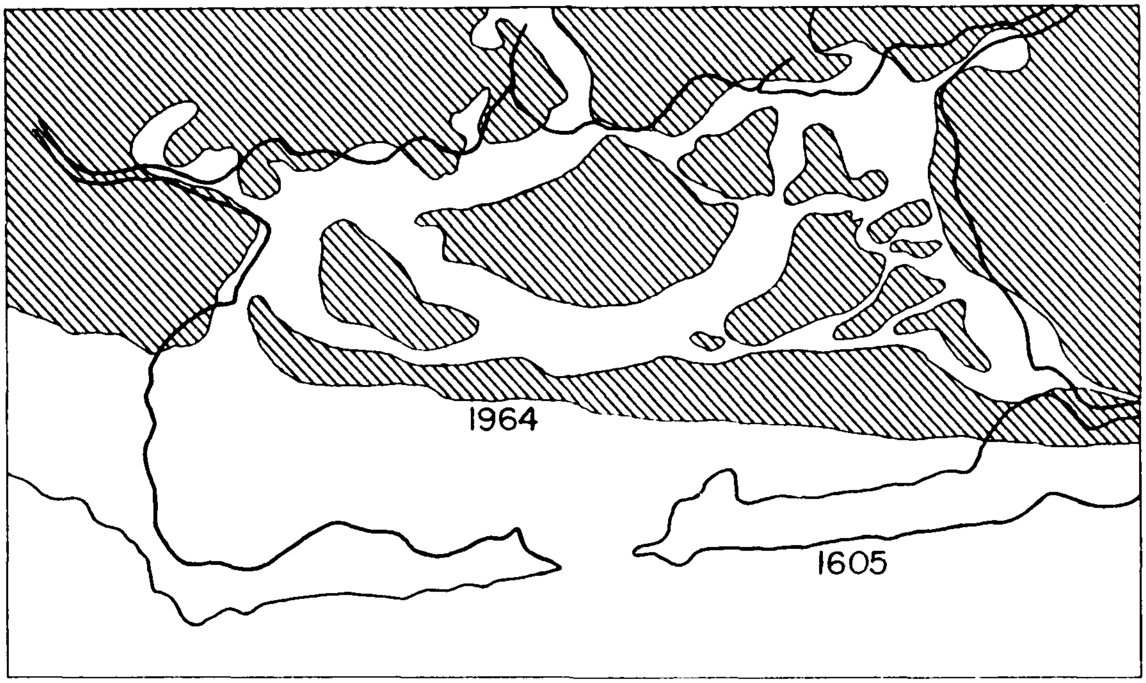


Figure 96. Overlay of Champlain's 1605 map and a 1964 topographic map of Nauset Harbor.

By the end of the 18th century, the Nauset Harbor area was very different from either 1605 or 1977. Des Barre (1764), a mapmaker for the Royal British Navy, produced a detailed map of the Nauset Spit system (Fig. 97), which showed both a change in orientation of the barrier and a change in the physiographic features from 1605. In 1764 Nauset Spit-Eastham was dissected into many small sections that are shown as irregular forms on the map in the appropriate location for a dune line. A close inspection of the shading notation used by Des Barre shows that these breaches were breaks in the dune line (washovers), rather than inlets which experienced tidal exchange. Seismic data collected along Nauset Spit-Eastham north of the present inlet (D. Aubrey, Woods Hole Oceanographic Institute, personal communication, 1980) and the presence of almost continuous salt-marsh peat beneath the dune line indicate that an inlet has not existed north of the present inlet within the recent past. These irregular features on Des Barre's map were dunes, while the shading between and westward of the dunes undoubtedly represented washovers. Nauset Spit either recently overwashed in 1764 and was very similar to its physiographic appearance in 1978 (i.e., remnant dunes) or the spit had overwashed many years earlier and these features represented new dunes forming on washovers.

Des Barre's map shows a large salt marsh in the center of Nauset in approximately the same position as the present marsh. Also, the main channel into Nauset Harbor curves to the south as it does today, very close to Nauset Heights. Nauset Spit-Orleans is present on the 1764 map, but is much shorter than noted in 1605.

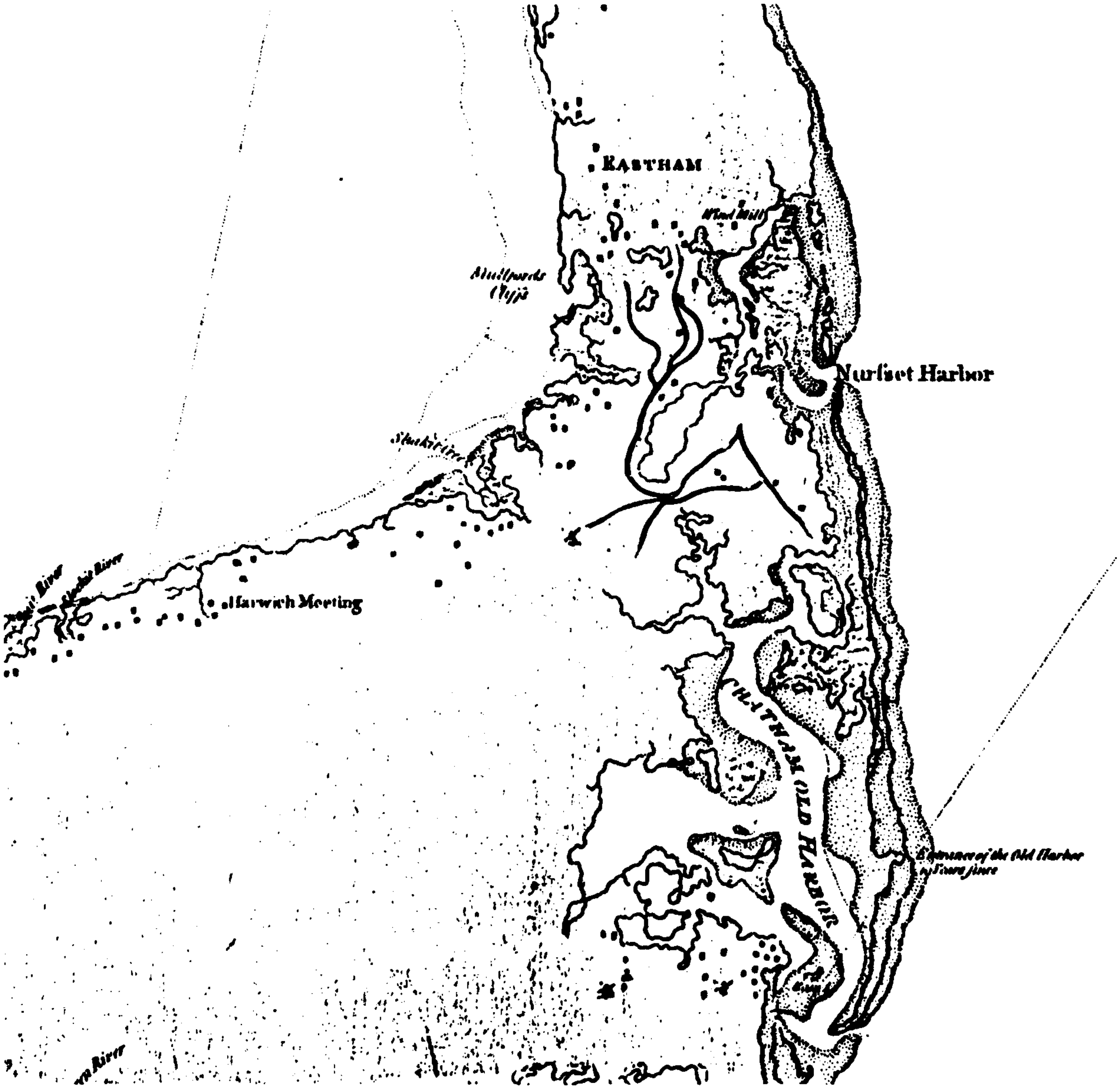


Figure 97. Des Barre's 1764 chart of Nauset Spit (courtesy Atheneum) Library of Boston).

The next significant map of Nauset Spit is the first U.S. Coast Survey map made in 1856 (Fig. 98). The inlet into Nauset Harbor had migrated to the south near Nauset Heights by this time, and the south spit had been completely eroded. The large salt marsh in Nauset Harbor was well developed with most of the present features easily identifiable. As the northern spit extended to the south in a more landward position, a large marsh island became fused to the spit, separated by sandflats covered only during very high tides. The channel into Nauset Harbor had been diverted far to the south.

c. <u>North Beach</u>. The first description of the North Beach section of the Nauset Spit system was written in 1602 by Archer, a member of Gosnold's crew on an exploratory voyage (Massachusetts Historical Society Collections, 1843).

Figure 98. U.S. Coast Survey map of Nauset Spit-Eastham, 1856.

Archer noted that after passing Tucker's Terror, which must have been the ebb tidal delta off Nauset Inlet (Nickerson, 1931), Gosnold anchored to the lee of Point Care in 8 fathoms of water (Fig. 94). Point Care must have been the south spit at Nauset Harbor formed by the drumlin noted by Champlain 3 years earlier. This glacial deposit and the ebb tidal delta of Nauset Inlet must have projected considerably eastward to afford Gosnold a calm anchorage. Archer referred to many "breaches" around the ship at this site, some of which the crew tested to see if it would be possible to enter the bay to obtain freshwater. Finding all these breaches too shallow for passage, Gosnold sailed south "passing by the breach of Point Gilbert" and noting two more inlets to the south. Archer recorded the inlet at Point Gilbert at 40° 2/3', approximately opposite the site of Chatham Light (Fig. 3).

Champlain visited North Beach 4 years later on his second voyage to Cape Cod. After a brief stop at Nauset Harbor, Champlain continued south, attempting to come ashore on the ocean beach. Unable to land, Champlain took the advice of Indians and sailed south, rounding a long spit which he called Cape Batturier and landing at Port Fortune (Stage Harbor) in Chatham. The detailed map that Champlain constructed for Port Fortune (Fig. 99) suggests that a spit east of Chatham was attached to the mainland at Allen Point (Fig. 3).

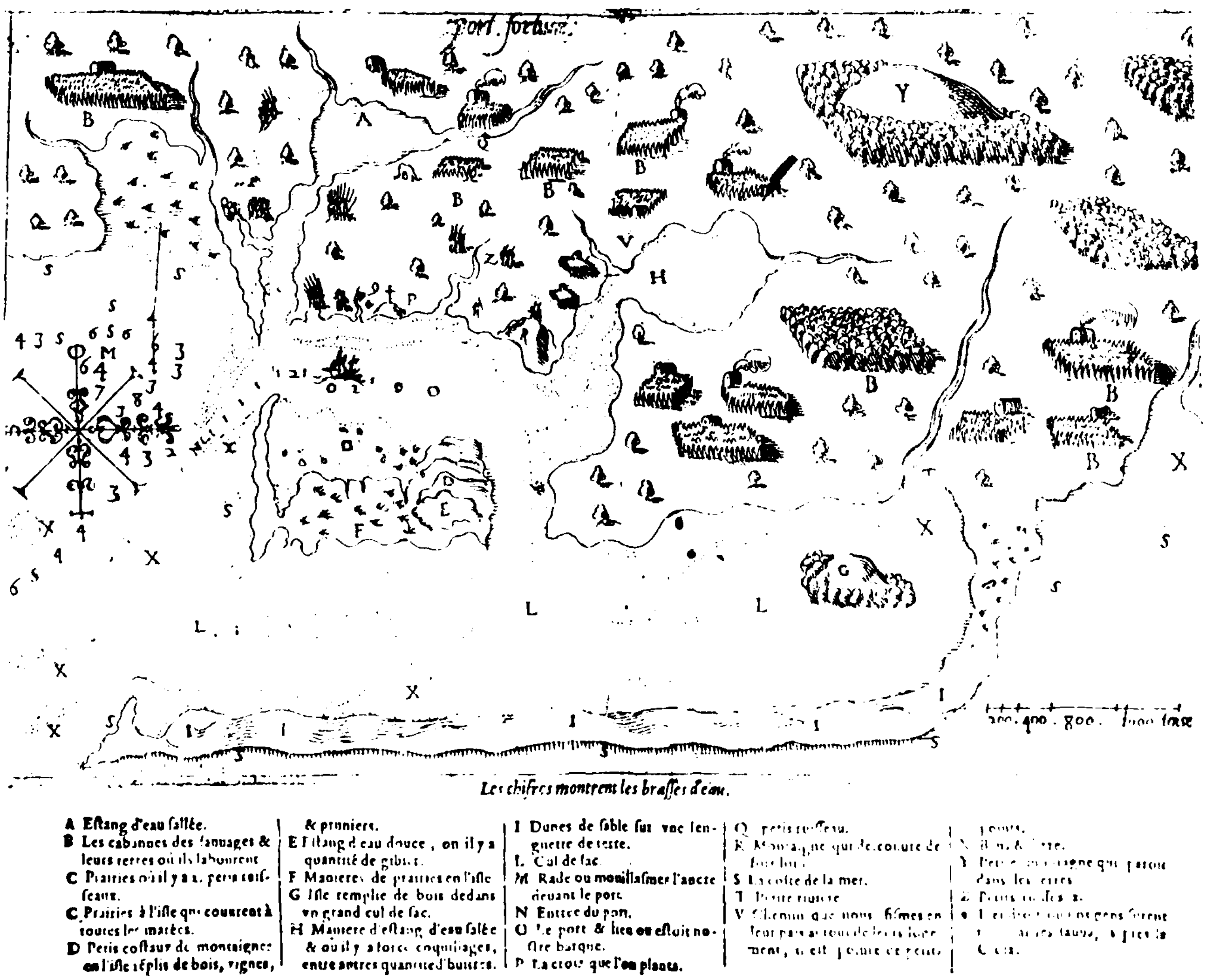


Figure 99. Champlain's 1607 map of Port Fortune (Stage Harbor, Chatham) (from Biggar, 1922).

Champlain did not provide any detail of the coastline between Mallebar (Nauset Harbor) and the northern point of Batturier (at Allen Point). On a later map in 1607, undoubtedly made from the same information collected in 1605 and 1609 (Fig. 100), this section was shown as an indentation in the otherwise smooth shoreline. Considering the care with which Champlain mapped other areas of the American coast, this omission is surprising. It is possible that in sailing through Tucker's Terror and around Point Care, Champlain was taken too far to sea to allow detailed views of this part of the Nauset coastline.

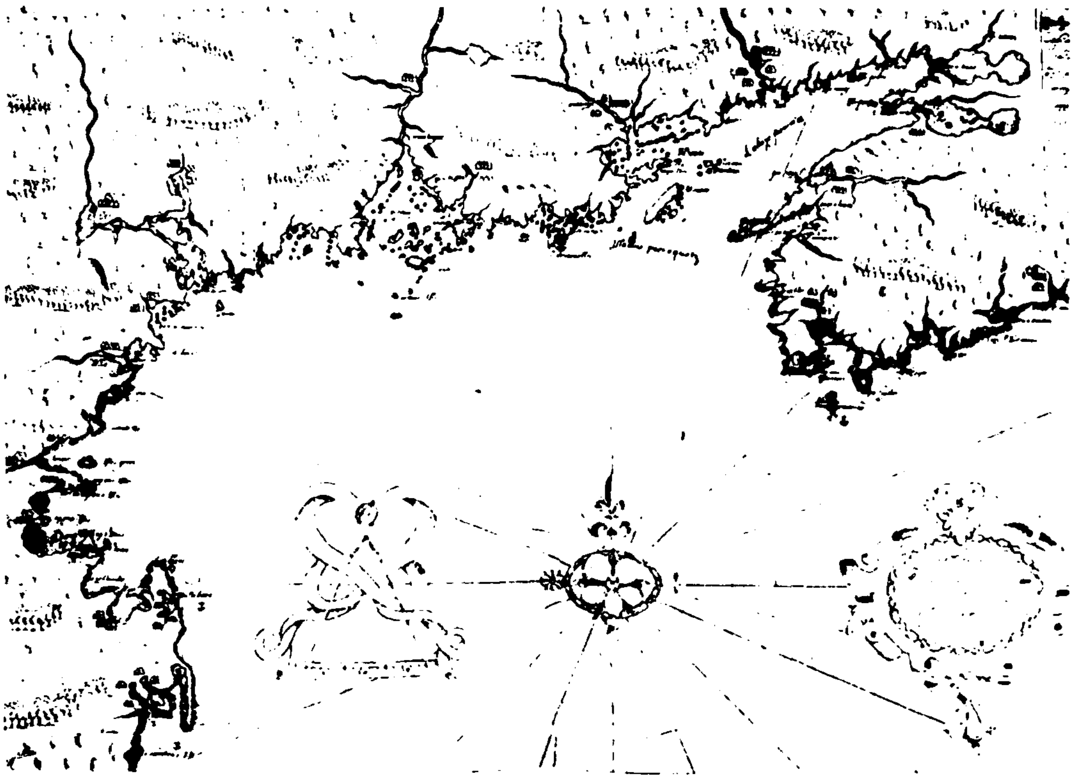


Figure 100. Champlain's 1607 chart of Cape Cod (courtesy of Library of Congress) (from Morison, 1972).

Nickerson's (1931) composite map made from accounts in the early 1600's shows several inlets through North Beach north of the spit (Cape Batturier) mapped by Champlain (Fig. 94). One of these inlets has been clearly marked by the stranding of the ship, the *Sparrow-Hawk*, in 1626. Sailing without adequate provisions, the *Sparrow-Hawk* was forced to land by angry passengers (Otis, 1864). The sudden landing proved fatal when the ship became entrapped on the shoals around an inlet through North Beach 1 mile south of Pochet Island. Rising tides freed the ship but only drove it onto the shoals inside the harbor. The ship was abandoned and covered with sand as the inlet channel shifted southward. This inlet was also noted by Hudson in 1600, Dermier in 1619, and Bradford in 1622 (Nickerson, 1931).

In 1863, 237 years after the grounding of the *Sparrow-Hawk* in Pleasant Bay, the same ship was exposed on the ocean beach (Otis, 1864). Salt marsh had developed around the ship, which had been firmly fixed in the sand. This

marsh was subsequently overwashed, and dunes had formed on washovers covering the ship. Finally, storm waves eroded the dune line, exhuming the *Sparrow-Hawk*. North Beach had receded landward by the width of the barrier, plus the distance from the bayward edge of the marsh to the stranded ship. Therefore, the time frame for barrier rollover in this region was less than 237 years.

If the interpretation of Champlain's map of Port Fortune is correct and the spit east of Chatham did join the mainland at Allen Point, and if inlets recorded by Gosnold (and others) and the sinking of the *Sparrow-Hawk* are correct, it appears that North Beach was highly dissected between 1600 and 1620. It seems likely, from more recent data, that the spit was breached in a single location some years earlier (perhaps between 1550 and 1580) and that sections of the barrier south of the principal inlet, deprived of adequate sand, were migrating rapidly toward the mainland. Nickerson's composite map (Fig. 94) does not differ significantly from maps of North Beach 30 years after the 1846 breach through the continuous barrier spit. The problems early explorers had landing in Chatham (Gosnold, Champlain, the *Sparrow-Hawk*), or even passing by the area (Gosnold, Champlain, the *Mayflower*), were undoubtedly caused by many poorly maintained inlets through North Beach--a situation similar to the "ruined" harbor mentioned by Mitchell in the 1870's.

The next available map of the North Beach area was made by Southack in 1717 (Fig. 101). Although the scale of this map is badly distorted, a waterway between Nauset Marsh and Pleasant Bay is clearly evident. Surprisingly, Champlain (and others) did not record this channel, possibly because it was not navigable and therefore of little importance. Southack's map also shows that North Beach was again a continuous spit extending along the mainland well to the south of Chatham.

Des Barre's 1764 map, which shows the same details as the Southack map, positions the end of North Beach approximately east of Tern Island (Figs. 3 and 97). The spit extended 3.2 kilometers to the south in 30 years (Des Barre, 1764). Several other accounts of the same period document the rate at which the spit built to the south. Two accounts state that between 1742 and 1772 the spit extended at a rate of 1.6 kilometers per 12 years and 1.6 kilometers per 8 years (Hitchcock, 1835).

If North Beach had extended from a point 3.2 to 8 kilometers southward by 1780, the inlet in 1742 must have been just south of the 1626 inlet site, located by the stranding of the *Sparrow-Hawk*. This inlet marks the beginning of the second cycle since the late 1500's at a point south of the 1626 inlet.

During the early part of the 19th century, North Beach continued to extend southward. In 1817 North Beach began at Nauset Harbor and extended 12.8 to 14.4 kilometers to the south (approximately 9.6 to 11.2 kilometers south of the glacial headlands at Orleans) (Blunt, 1817). Between 1765 and 1835 the spit had extended 4.8 kilometers in length (Hitchcock, 1835). Another account stated that between 1829 and 1849, 3.2 kilometers was added to the Spit (Davis, 1849).

By 1851 North Beach extended beyond Morris Island (Mitchell, 1873). The *Minot Gale* in 1851 breached the spit across from Allen Point (U.S. Coast Survey Annual Report, 1851). Major erosion of North Beach did not, however,

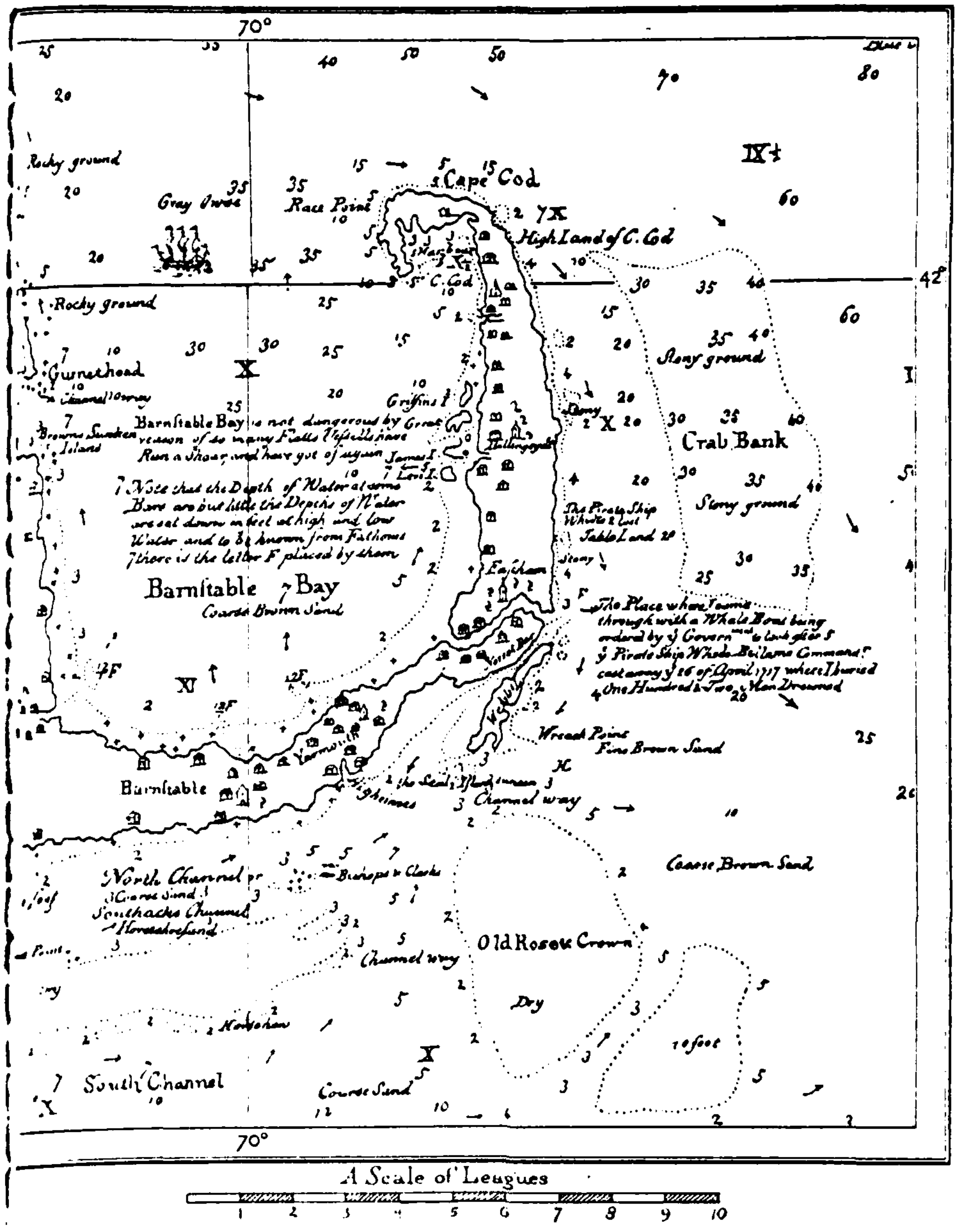


Figure 101. Southack's 1717 map of Cape Cod (courtesy of Harvard Museum of Comparative Zoology) (from Goldsmith, 1972).

take place until a storm in 1869 created a larger permanent inlet through the barrier (Mitchell, 1873). By 1851 North Beach had begun its third inlet migration cycle in recorded history. At this time, the passage between Pleasant Bay and Nauset Harbor was closed except at very high tides (Freeman, 1858).

In 1871 Henry Mitchell of the U.S. Coast Survey was assigned to document the rates of erosion of the barrier spit protecting Chatham. From measurements taken between 1847 and 1872, Mitchell calculated a loss of 129 hectares and as much as 305 meters from North Beach (Mitchell, 1873). The shoreline

retreated 1.58 kilometers landward by 1886. The glacial headlands of Chatham were exposed to the sea and eroded rapidly. During 1 year the cliff near Chatham Light eroded 31 meters (Mitchell, 1875). At least one street was lost from the town as waves eroded developed land (Goldsmith, 1972).

The cycle of inlet formation, dissolution of the southern part of the spit after breaching and migration of the inlet to the south, has occurred three times since explorers first visited Cape Cod. The complete cycle takes between 100 and 175 years. North Beach has not been breached since 1846; a new inlet-spit elongation cycle appears imminent (Onysko, 1978).

There is no record of inlets north of the 1626 *Sparrow-Hawk* site, nor is there reason to believe that the initial inlet of the second cycle was formed as far north as the 1626 inlet. The landward migration of North Beach was, therefore, controlled predominantly by overwash processes north of the 1626 inlet, where the barrier is backed by an extensive salt marsh or glacial headlands. All barrier features south of the *Sparrow-Hawk* site are younger than 354 years, having been influenced by inlet dynamics and spit regeneration during this time.

4. Historic Changes: Quantitative.

a. Introduction. The entire Nauset Spit system has been constructed by longshore sediment transport from the eroding outwash plains of Eastham, Wellfleet, and Truro, and can be reasonably divided into three major units: Nauset Spits--Eastham and Orleans fronting Nauset Marsh; the section of North Beach north of the 1846 inlet (Old North Beach); and North Beach south of the 1846 inlet (New North Beach; Fig. 3). The present spit north of Nauset Inlet (2.7 kilometers; Fig. 2) has not been subject to inlet dynamics in recent times. The area between Nauset Inlet and Nauset Heights (1.8 kilometers) has eroded and rebuilt several times in recorded history by inlet migration. Old North Beach (17.9 kilometers) has not been affected by inlet breaching since 1868. The southern 2 kilometers of North Beach developed as a result of southerly migration of the 1626 inlet. New North Beach (6.7 kilometers) has been created since 1846 and does not have remnant salt-marsh peat below surficial features.

There have been several studies of shoreline changes along the Atlantic coast of Cape Cod. Field surveys of Nauset Spit were conducted by the U.S. Coast Survey during the 19th century. Nauset Spit-Eastham was surveyed in 1856 and 1886; Old North Beach was surveyed in 1868 and 1886; and New North Beach was surveyed in 1851 and 1886. Marindin (1889) compared these surveys to calculate the rate of shoreline erosion along the spit system (Table 40). "T" sheets were published from these data for New North Beach in 1851 and 1886, Old North Peach in 1868, and Nauset Spit-Eastham in 1856. The transects surveyed by Marindin in 1886 along the Nauset Spit-Eastham section were reoccupied in 1957 by Zeigler, et al. (1964), and comparisons were made to earlier surveys (Table 40). An aerial photography study of shoreline changes was recently conducted along the entire outer Cape (Gatto, 1979). The shoreline position of two locations on each of Nauset Spit-Eastham, Old North Beach, and New North Beach was recorded from a series of photos taken between 1938 and 1974. The rate of shoreline erosion at these positions appears in Table 40.

Table 40. Erosion rates along glacial cliffs and the Nauset Spit system (m/yr).

Area	Data source			
	Marindin (1889)	Zeigler, et al. (1964)	Gatto (1979)	This report
Nauset Cliffs	$\bar{X}$ = 1.0 (1868-86)	$\bar{X}$ = 0.7 (1868-1957)	1.8 3.8 2.1 (1938-74)	
Nauset Spit-Eastham	$\bar{X}$ = 0.1 (1856-86)	$\bar{X}$ = 1.3 (1856-1957)	1.3 (1938-74)	$\bar{X}$ = 0.9 (1856-1978) $\bar{X}$ = 1.0 (1856-1952) $\bar{X}$ = 1.2 (1938-78)
Old North Beach	$\bar{X}$ = 2.4 (1868-86)		2.0 0.9 (1938-74)	$\bar{X}$ = 1.5 (1868-1978) $\bar{X}$ = 0.7 (1868-86) $\bar{X}$ = 1.6 (1938-78)
New North Beach	-------[1]		5.1 5.9 (1938-74)	$\bar{X}$ = 5.8 (1938-78)

[1]Included with Old North Beach.

This study is the first attempt to describe quantitatively changes in physiographic features on Nauset Spit during the past 127 years. The U.S. Coast Survey Maps for 1851, 1856, 1867, 1868, and 1886 and aerial photos taken in 1938, 1941, 1952, 1964, and 1978 were used to map ocean and bay shoreline positions and vegetative units. Aerial photos for 1938, 1952, and 1978, which were taken after major storms, are used in this study. These photos bias the results in favor of washovers, because in many cases dune and shallow-buried salt-marsh plants may have been alive and recovering from burial, but were not visible on the photos. If these photos were taken during calm periods, washovers would be much less prominent. These photos were chosen because they were complete for the spit system and showed the magnitude of overwash processes. Photos taken in 1941 and 1964, although of inferior quality, were used to expand the data obtained from 1938, 1952, and 1978 photos.

b. Methodology. The principles and accuracy problems of map construction from historical aerial photos and coastal charts were reviewed by Anders and Leatherman (1980), so only a brief summary of the methodology will be presented. A technique of map construction from charts and aerial photos was devised with the assistance of National Ocean Survey (NOS). The first step in the procedure is to locate stable control points on each chart or photo. The same points are marked on corresponding NOS T sheets. Road intersections and buildings are the most accurate points due to their fixed positions. Manmade structures, however, are not always present on barriers or the mainland shoreline. Natural features which have remained stable over the duration of the mapping interval can be used as alternative points. A minimum of four control points were located and plotted on each photo of the Nauset Spit system and on the corresponding T sheet.

In the next step, a base map was produced onto which T sheet or photo data could be transferred. The state plane coordinate system intersections on the T sheets served as a set of primary control points. Manmade and natural points acted as secondary controls. The relative position of each control point was determined with an X-Y digitizer. Since state plane coordinates were known for the primary control points, a program (CONVERT), developed by NOS, was used to transform all digitized secondary control points into state plane format. These points were then plotted onto mylar at a 1:10,000 scale by means of a second computer program (P2NDPT) and a Calcomp plotter. The mylar sheet became the base map onto which shoreline data were transferred.

Concurrent with the production of the base maps, aerial photos were annotated to highlight ocean and bay shorelines, dunes, shrubs, marshes, and washovers. Distinctions were not made among dunes, shrubs, and washovers on the early U.S. Coast Survey charts, and these units were combined into one category. All data were transferred onto base maps with a Bausch and Lomb zoom transfer scope (ZTS).

Individual photos were optically overlaid on the base maps. Scale and stretch adjustments were made until the optimal fit between the control points on the photo and base map was achieved. Perfect alinement of all control points was not possible, because the ZTS does not correct for tilt. Once the best possible fit was achieved, however, most of the distortion was removed. After the base maps were completed, coordinates were determined using the X-Y digitizer for shorelines and vegetation community boundaries. It was possible to produce any desired map or set of overlay maps with different scales, levels of detail, or line type with the plotting programs.

The length of each major unit of the Nauset Spit system was calculated from each historical map. Shoreline changes were measured at 61-meter (200-foot) intervals along the entire spit system. The average, minimum, and maximum barrier widths were calculated at 305-meter (1,000-foot) intervals. Areas for dune, salt marsh, and shrub communities, and for washovers and supratidal sandy environments, were determined with a polar planimeter on a large-scale map (1:2,400). The location of loss or gain of total barrier area was determined for sequential pairs of overlaid maps (1:12,000) using a dot grid (256 dots per square inch). Distinctions were made for areas gained and lost along the ocean, bay, and at the spit terminus. Sequential map overlays (1:12,000) were used to delineate the location of dunes and salt marshes that were lost and those that developed between the mapping periods; these changes were quantified with a dot grid.

c. Nauset Spit-Eastham. The southern 2.1 kilometers of Nauset Spit-Eastham has changed dramatically in the last 122 years due to the migratory characteristics of Nauset Inlet (Fig. 102; Table 41). Only a single spit extended southward from the Eastham headlands near the Nauset Coast Guard Station in 1856. The destruction of the drumlin described by Champlain in 1605 (Fig. 95) led to the landward migration and dissolution of the south spit. Salt marshes to the lee of this spit were buried by shifting sands during the 1830's (Nickerson, 1931). The north spit extended southward to a position west of the former south spit. By 1856 Nauset Inlet was located at the base of Nauset Heights and the north spit was 4.9 kilometers long.

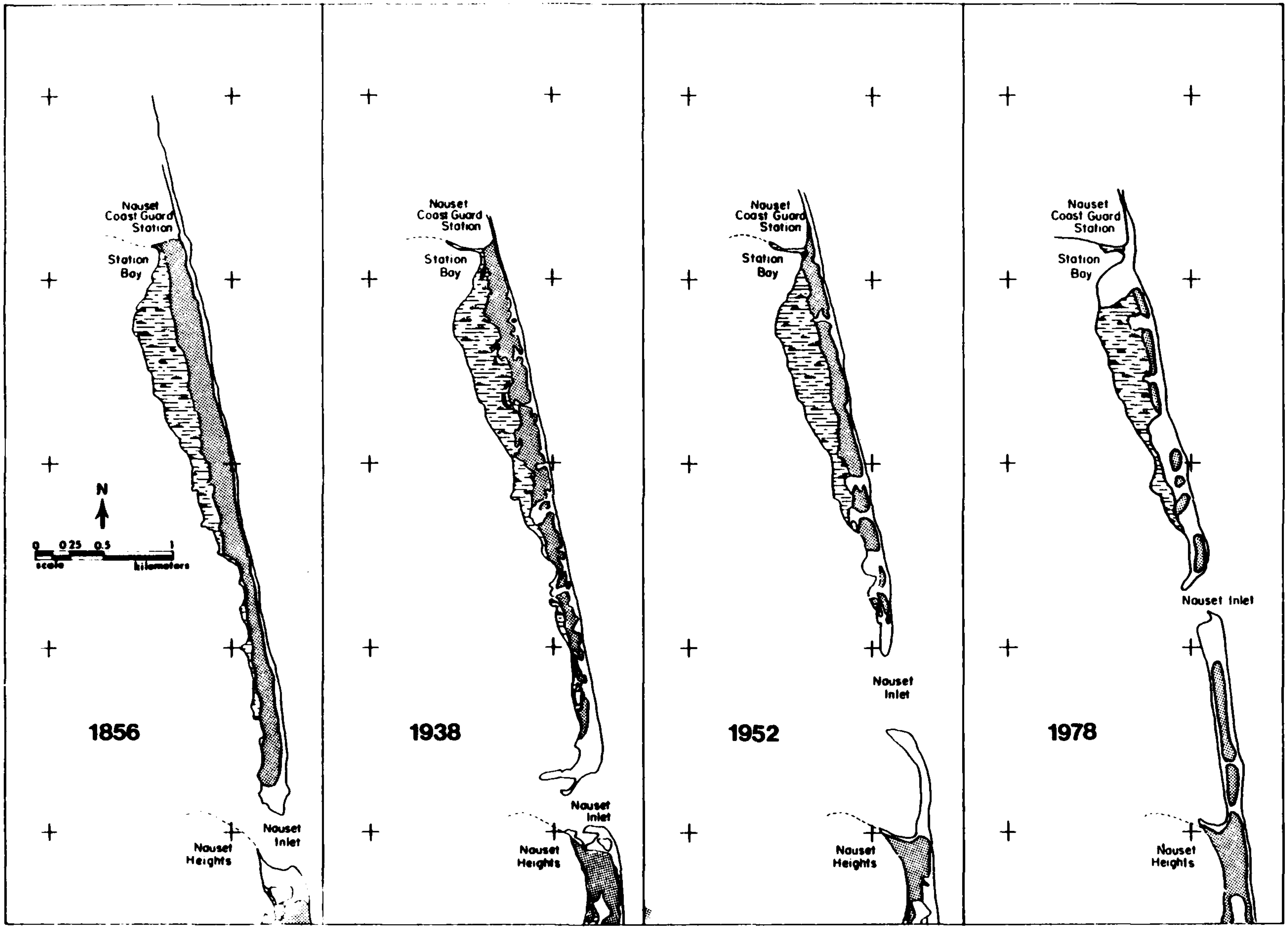


Figure 102. Maps of N. iset Spit-Eastham showing physiographic features (from an 1856 chart and aerial photos taken in 1938, 1952, and 1978).

Table 41. Length of barrier units between 1851 and 1978.

Area	1851, 1856, 1868 (km)	1886 (km)	1938 (km)	1952 (km)	1978 (km)
Nauset Spit-Eastham	4.9	----[1]	4.4	3.5	2.8
Nauset Spit-Orleans	0.0	0.0	0.1	0.9	1.9
Old North Beach	11.3	11.3	11.3	11.3	11.3
New North Beach	8.5	6.7	4.1	5.2	6.7

[1]No available maps.

Nauset Inlet had migrated north by 1938 and a small spit, 70 meters long, extended north from Nauset Heights. Nauset Inlet, which was only 236 meters wide in 1938, continued to migrate northward. Between 1938 and 1952, the inlet moved 1153 meters to the north by means of a breach that formed and widened approximately 800 meters north of the inlet. The isolated spit section to the south then eroded.

Although Nauset Spit-Orleans eroded back to Nauset Heights between 1938 and 1941, the spit rapidly extended to the north in the ensuing 37 years. Between 1941 and 1952, Nauset Spit-Orleans extended 809 meters at a rate of 73.5 meters per year. More than 1023 meters were removed from the southern end of Nauset Spit-Eastham during this period. In the years between 1952 and 1971, Nauset Spit-Eastham again built to the south in a position west of Nauset Spit-Orleans, incorporating a large salt-marsh island into the body of the barrier. The channel into Nauset Harbor followed a circuitous path between the two spits and passed below Nauset Heights into Nauset Harbor. In 1972 a new inlet was driven through Nauset Spit-Eastham during a northeaster in the approximate location of the earlier inlet (1940's). Again the isolated southern part of Nauset Spit-Eastham eroded except where dunes had formed on the salt marsh that had been incorporated into the spit (New Island; Fig. 102). The inlet continued to move northward so that after the February 1978 northeaster, Nauset Spit-Eastham was only 2800 meters long. Nauset Spit-Eastham receded 706 meters northward (27 meters per year) between 1952 and 1978, while Nauset Spit-Orleans extended 1038 meters (40 meters per year). Concurrently, Nauset Inlet was narrowed from 606 meters in 1952 to 274 meters in 1978.

Spit growth or truncation is dependent on the direction of net littoral transport, which appears to be variable through time near Nauset Inlet. The northward migration of the inlet in recent years is probably the result of a southerly shift in the nodal point to the vicinity of Nauset Heights and a net northward movement of sediment along Nauset Spits--Eastham and Orleans (Fisher and Simpson, 1979; Wright and Brenninkmeyer, 1979; Anders and Leatherman, 1980).

Erosion along the Nauset Spit-Eastham shoreline has varied through time averaging 0.9 meter per year between 1856 and 1978 (Fig. 103; Table 42). The

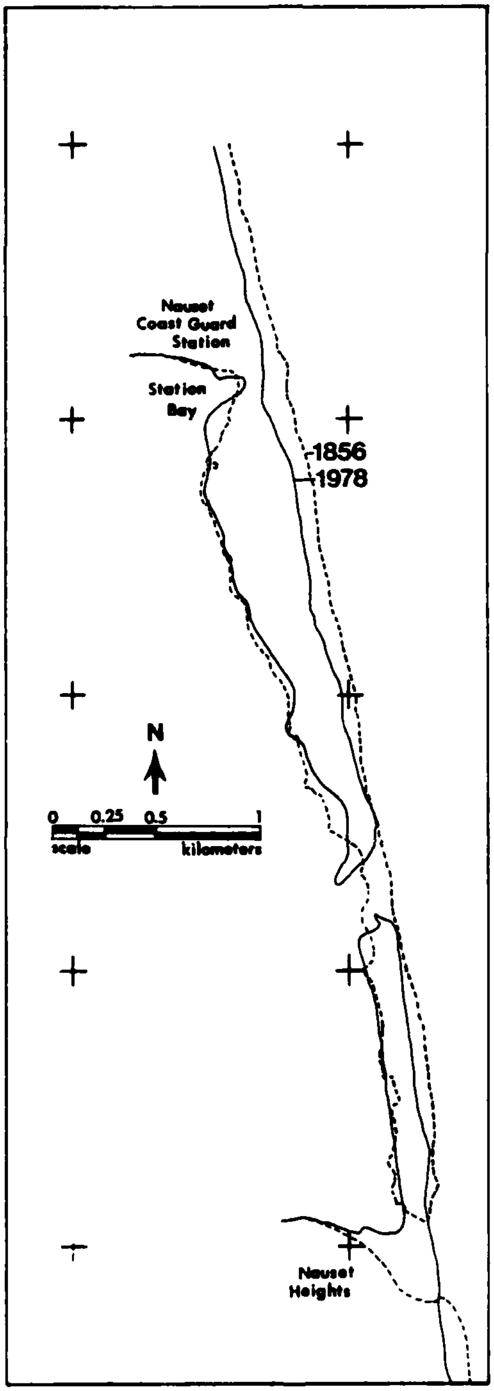


Figure 103. Map overlay of Nauset Spit-Eastham, 1856 and 1978.

Table 42. Erosion rates along the Nauset Spit system using serial map overlays.

Area	1851, 1868-86 (m/yr)	1856-1938 (m/yr)	1886-1938 (m/yr)	1938-52 (m/yr)	1952-78 (m/yr)	1851, 1856, 1868-1978 (m/yr)
Nauset Spit-Eastham		0.7		3.3	0.5	0.9
Old North Beach	0.7		1.7	2.7	1.3	1.5
New North Beach	22.8			6.2	5.5	5.8

most rapid rate of erosion occurred between 1938 and 1952 when an average of 3.3 meters of beach per year was lost. Between 1952 and 1978, the rate slowed to 0.5 meter per year, although in some areas as much as 10 meters of shoreline erosion occurred during the February 1978 storm. The 40-year erosion rate of 1.2 meters per year correlated well with 1.3 meters per year obtained by Zeigler, et al. (1964), and Gatto (1979) (Table 40). The erosion rate obtained by Marindin (1889) from field surveys between 1856 and 1886 (0.1 meter per year) reflects a period when Nauset Spit-Eastham experienced little erosion. These data agree with the relatively low rate of erosion obtained in this study (0.7 meter per year) using measurements taken from both the 1856 maps and the 1938 photos.

The average width of Nauset Spit-Eastham has consistently decreased since 1868 (Table 43). Comparing only that part of the spit north of the 1978 inlet, overall barrier width has decreased from 430 meters in 1868 to 293 meters in 1978. Shoreline erosion removed 110 meters from the oceanfront which accounts for most of the narrowing of the spit. During the 122-year period, 11.9 hectares was lost from the bay shoreline of the barrier, but most of this loss occurred in the southern 2.1 kilometers of the spit where tidal currents eroded marsh and sandflat environments (Table 44). Additions to the back of the barrier by rhizome outgrowth onto tidal sedimentation and by overwash totaled 18.4 hectares. This new substrate was deposited locally in the southern 2.1 kilometers of the spit and these areas have been destroyed as the inlet migrated northward.

The width of Nauset Spit-Eastham presumably exceeds the critical minimum barrier width at which washover deposits can add significant amounts of substrate to the back side of the barrier. In 1978 a major overwash occurred along Nauset Spit-Eastham. Although 26.9 hectares of washover was mapped after the storm (Table 45), only 1.7 hectares of new substrate was added to the bay side of the barrier; 25.2 hectares of washover was deposited on previous dune and salt-marsh environments.

Nauset Spit-Eastham is composed of four primary environments: dune, salt marsh, washover, and sandy shoreline. The area of each environment was calculated for each map (Table 45; Fig. 102). The total supratidal area of Nauset Spit-Eastham has decreased by 48 percent in 122 years--from 152.8 hectares in 1856 to 78.9 hectares in 1978. All the environments except washovers have decreased dramatically in size.

Table 43. **Barrier width for each unit along the Nauset Spit system, 1851 to 1978.**

Area	Degree width	1851, 1856, 1868 (m)	1886 (m)	1938 (m)	1952 (m)	1978 (m)
Nauset Spit-Eastham	$\bar{x}$ [1]	337	--- [2]	223	291	293
	$\bar{x}$ [3]	430		379	338	293
	min	105		99	99	112
	max	623		551	511	468
Nauset Spit Orleans	$\bar{x}$				90	132
	min				63	85
	max				112	160
Old North Beach	$\bar{x}$	446	450	404	403	397
	min	68	173	169	121	85
	max	1196	1177	991	1030	997
New North Beach	$\bar{x}$	505	153	626	445	279
	min	220	43	446	180	74
	max	675	291	802	672	790

[1] Includes the entire length of Nauset Spit-Eastham.

[2] There are no 1886 maps available for Nauset Spit-Eastham.

[3] For comparison, includes only the section of Nauset Spit-Eastham north of the 1978 inlet.

Table 44. **Location of changes in total barrier area calculated from serial map overlays, Nauset Spit-Eastham.**

Year	Bay shoreline Loss (ha)	Bay shoreline Gain (ha)	Oceanfront Loss (ha)	Oceanfront Gain (ha)	Spit terminus Loss (ha)	Spit terminus Gain (ha)
1856 to 1938	3.0	13.8	36.7	0.0	0.0	0.0
1938 to 1952	5.7	2.9	3.0	0.0	22.7	0.0
1952 to 1978	3.2	1.7	7.8	0.0	12.6	2.1
1856 to 1978	11.9	18.4	47.5	0.0	45.3	2.1
Net[1]		6.5	47.5		33.2	

[1] Net loss for entire section = 74.2 hectares.

Table 45. **Area of barrier environments, Nauset Spit-Eastham.**

Year	Dunes (ha)	Dunes (pct)[1]	Washovers (ha)	Washovers (pct)	Marshes (ha)	Marshes (pct)	Sandy shorelines (ha)	Sandy shorelines (pct)	Total supratidal environments (ha)	Total supratidal environments (pct)
1856	75.1[2]		75.1[2]		57.0		20.7		152.8	
1938	50.2		10.4		51.9	-9	20.7	0	133.2	-13
1952	35.7	-29	7.8	-25	44.2	-8	15.5	-25	98.7	-26
1978	13.8	-61	26.9	+245	32.3	-27	5.9	-62	78.9	-20
Overall change		-73[3]		+159[3]		-43		-71		-48

[1] Increase or decrease in hectare change.

[2] The 1856 map does not differentiate between dunes and washovers.

[3] 1938 to 1978.

There was 73 percent less dune habitat in 1978 than in 1938. The location of dune destruction and development was determined from map overlays (Table 46). Although most dune area was lost as a result of shoreline erosion (48 percent), overwash played an important role in destruction of the dune line at Nauset Spit-Eastham (31 percent), particularly during the February 1978 northeaster. During the 122 years considered in this study, 84.4 hectares of dunes was leveled, while only 15.2 hectares of new dunes was developed. Most of these new dunes were built on washovers deposited on salt marshes (59 percent).

Table 46. Location of areas lost or gained for salt marshes and dunes on Nauset Spit-Eastham.

	1856-1938		1938-52		1952-78		1856-1978	
	(ha)	(pct)[1]	(ha)	(pct)	(ha)	(pct)	(ha)	(pct)
Salt marsh								
Lost to:								
Washover	1.7	16	3.5	28	13.1	94	18.3	49
Bay side	1.9	18	5.2	42	0.2	1	7.3	20
Dune	7.0	66	2.0	16	0.0		9.0	24
Terminus	0.0		1.7	14	0.7	5	2.4	6
Total lost	10.6		12.4		14.0		37.0	
Gained from:								
Washover	0.0		0.0		0.1	5	0.1	1
Bay side	4.6	84	0.4	4	2.0	95	6.8	55
Dune	0.9	16	4.5	96	0.0		5.4	44
Terminus	0.0		0.0		0.0		0.0	
Total gained	5.5		4.7		2.1		12.3	
Net change	-5.1							
Dune								
Lost to:								
Ocean	25.0	70	9.4	37	5.9	30	40.3	48
Washover	7.1	20	5.4	22	13.7	70	26.3	31
Salt marsh	0.9	3	4.5	18	0.0		5.4	6
Bay side	0.4	1	0.0		0.0		0.4	<1
Terminus	2.1	6	5.8	23	0.0		12.0	14
Total lost	35.5		25.1		19.6		84.4	
Gained from:								
Ocean and washover	0.0		2.7	57	1.3	72	4.0	26
Salt marsh	7.0	80	2.0	43	0.0		9.0	59
Bay side	1.7	20	0.0		0.0		1.7	11
Terminus	0.0		0.0		0.5	28	0.5	3
Total gained	8.7		4.7		1.8		15.2	
Net change	-26.8							

[1]Percentage of hectares (lost or gained).

The salt-marsh area also changed substantially in 122 years. There was a 43-percent decrease in area of marshes contiguous to the dune line between 1856 and 1978. A total of 37 hectares of salt marsh (73 percent) was lost mainly as a result of overwash- and washover-associated dune development. New

salt marsh developed on the bay side (55 percent) and on washovers (44 percent) that were initially colonized by dune vegetation that failed to survive because the washover elevations were only marginally supratidal.

From these data, it is evident that Nauset Spit-Eastham has decreased dramatically in size over 122 years. The southern 2.1 kilometers of the spit has been lost to inlet migration; the northern 2.8 kilometers has remained an unbroken unit, but has not maintained barrier width. Nauset Spit-Eastham is eroding at a rate of 1.2 meters per year, approximately twice the rate of cliff retreat north of the spit. This erosion rate appears to be discrete rather than continuous. Very slow erosion occurred between 1856 and 1886, while very rapid erosion resulted from one storm in 1978. Inlet dynamics are the major process dominating the southern part of the spit, and overwash is the dominant process in the northern part. During the period under consideration, overwash has only been important in the redistribution of barrier environments and not in the maintenance of barrier width.

d. Old North Beach. During the past 110 years, Old North Beach has not been affected by inlet dynamics. This region is delimited to the south by the location of the 1868 inlet and to the north by Nauset Heights at the southern end of Nauset Harbor (Figs. 3 and 104). The original breach through North Beach in 1846 occurred just south of belt F (Fig. 90), which was 2.4 kilometers north of the spit terminus in 1868. The 1626 inlet was approximately 8 kilometers from the southern end of the spit in 1868. Remnants of the inlet channel are not evident today because the barrier has migrated to a position landward of these features.

Shoreline changes along Old North Beach during the past 110 years have varied from erosion of 2.2 meters per year in the center of the section to accretion by as much as 0.4 meter per year at the spit ends. Erosion rates for Old North Beach averaged 1.5 meters per year between 1868 and 1978 (Table 42; Fig. 105). Marindin (1889) calculated the erosion of North Beach at a rate of 2.4 meters per year during this same period (Table 40). This calculation is an average rate for North Beach and includes the island south of the 1868 inlet, which eroded at rates of more than 20 meters per year.

Since 1886 Old North Beach has consistently eroded landward. The greatest retreat occurred between 1938 and 1952 when an average of 2.7 meters of shoreline was lost per year. Between 1938 and 1978, erosion averaged 1.8 meters per year, which correlates well with Gatto's (1979) rates of 2.0 and 0.9 meter per year between 1938 and 1974 for two locations along this section (Table 40).

During the past 110 years, an average of 165 meters of shoreline was lost along Old North Beach, but the total area decreased only 6 percent from 450.2 hectares in 1868 to 421.5 hectares in 1978 (Table 47). Along the oceanside, 184.5 hectares was eroded; 62.9 hectares was lost from areas along the bay side as a result of tidal currents eroding salt marshes and washovers (Table 48). The average barrier width was reduced only slightly during this same time period (Table 43). In 1868 the width of Old North Beach averaged 446 meters; after 110 years, the same section had narrowed only 50 meters. The widest point of Old North Beach decreased in width from 1196 meters to 997 meters as a result of shoreline erosion without commensurate expansion on the

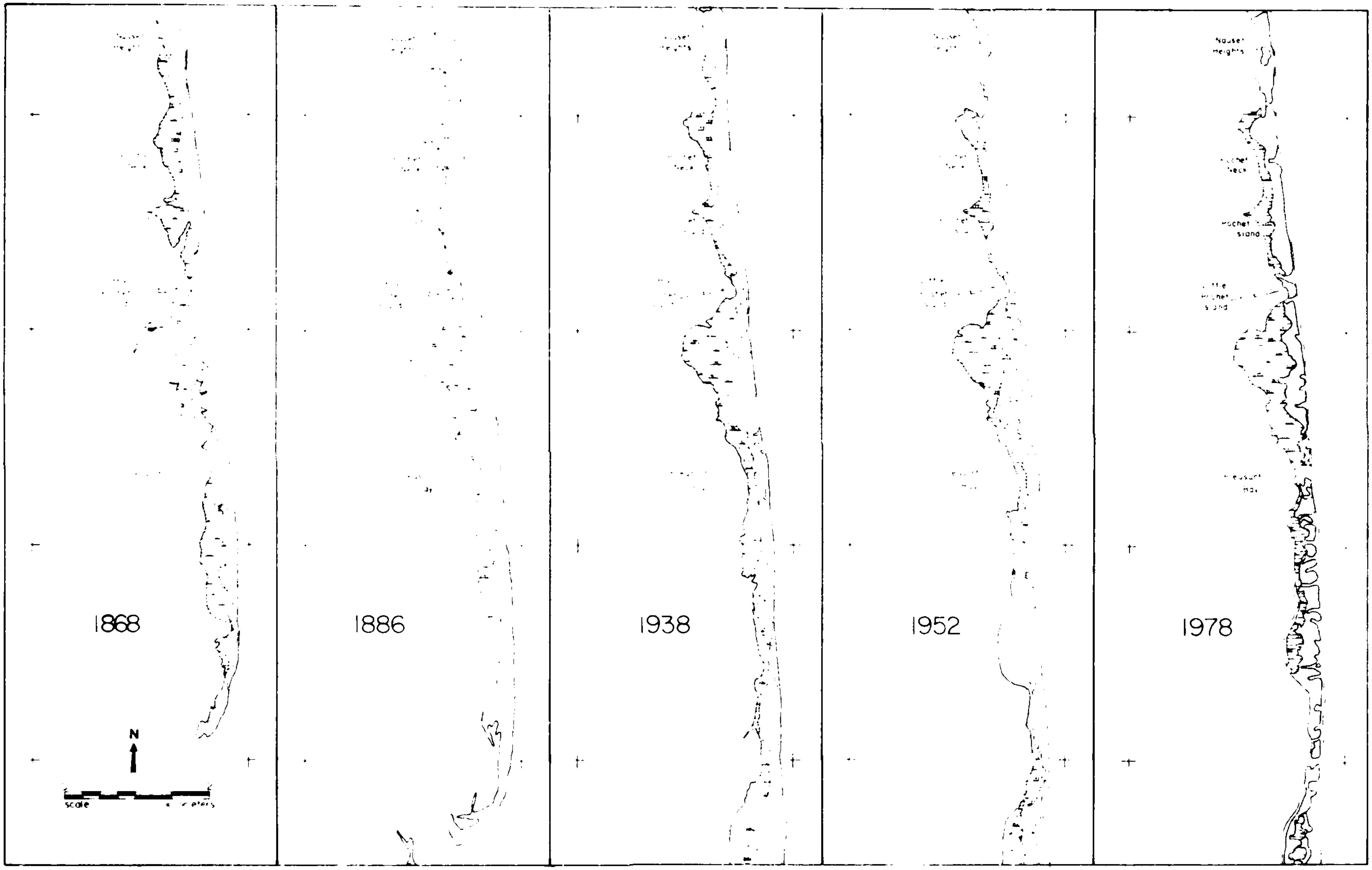


Figure 104. Evolution of Old North Beach, 1868 to 1978.

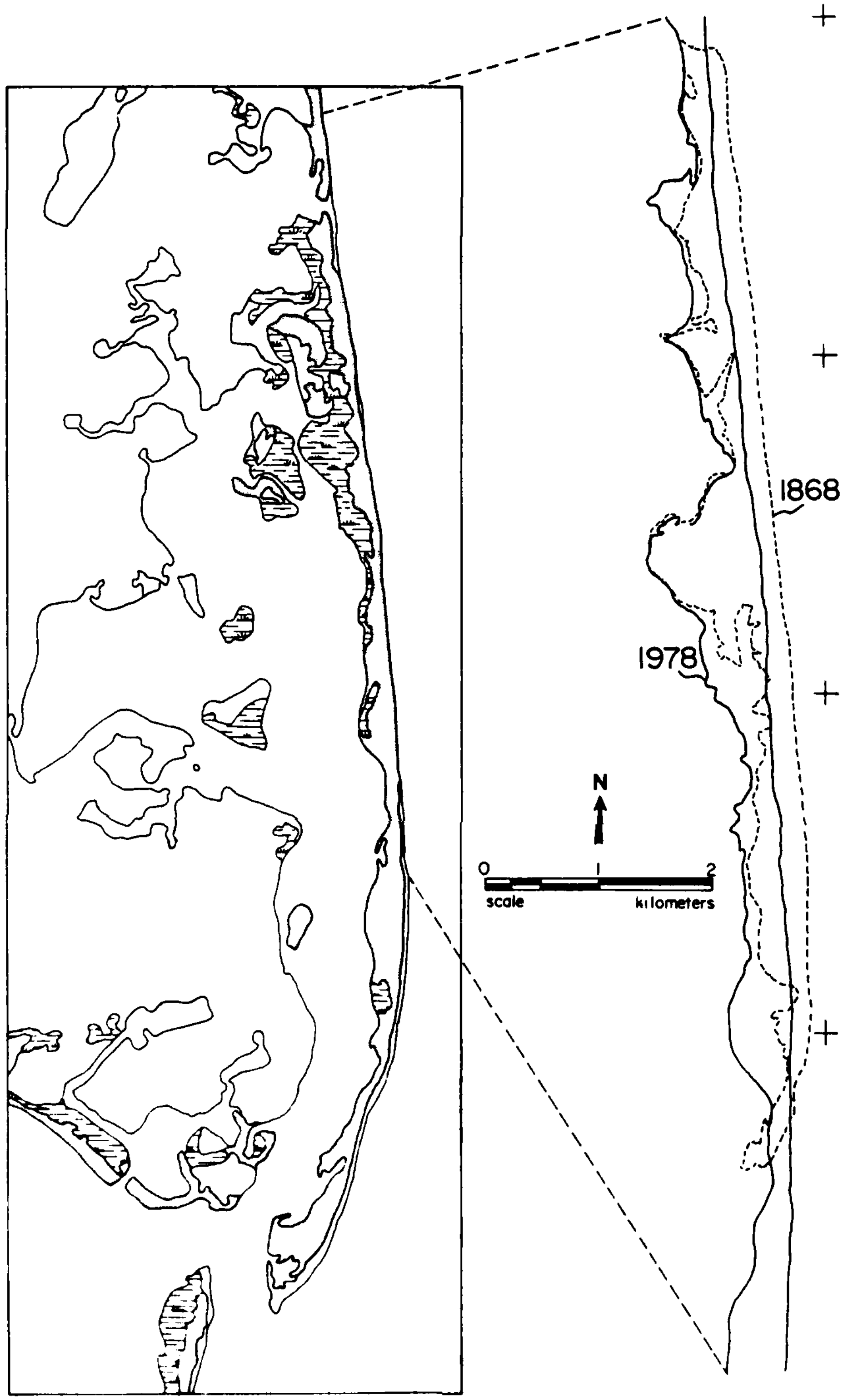


Figure 105. Shoreline erosion of Old North Beach, 1868 to 1978.

Table 47. Area of barrier environments, Old North Beach.

Year	Dunes (ha)	Dunes (pct)[1]	Washovers (ha)	Washovers (pct)	Marshes (ha)	Marshes (pct)	Shrubs (ha)	Shrubs (pct)	Sandy shorelines (ha)	Sandy shorelines (pct)	Total supratidal environments (ha)	Total supratidal environments (pct)
1868	194.3[2]		194.3[2]		193.7		-----[2]		62.2		450.2	
1886	191.7[2]	-1	191.7[2]	-1	182.8	-6	-----[2]		95.9	+54	470.4	+4
1938	162.6		67.4		148.3	-19	7.8		36.3	-62	422.4	-10
1952	133.2	-18	137.3	+104	123.9	-16	10.4	+33	57.0	+57	461.8	+9
1978	187.3	+41	28.5	-79	138.4	+12	20.7	+99	46.6	-18	421.5	+9
Overall change		+11		+11		-29		+165		-25		-6

[1] Increase and decrease in hectares.

[2] The 1868 and 1886 maps do not differentiate dunes, washovers, and shrubs.

Table 48. Location of changes in total barrier area calculated from serial map overlays, Old North Beach.

Year	Bayshore Loss (ha)	Bayshore Gain (ha)	Oceanfront Loss (ha)	Oceanfront Gain (ha)	Spit terminus Loss (ha)	Spit terminus Gain (ha)	Total Loss (ha)
1868 to 1886	21.8	31.9	26.7	3.1	0.0	33.7	
1886 to 1938	7.8	44.0	84.2	0.0	0.0	0.0	
1938 to 1952	10.4	71.0	27.9	6.7	0.0	0 0	
1952 to 1978	22.9	29.9	50.9	3.6	0.0	0.0	
1868 to 1978	62.9	176.8	184.5	13.4	0.0	33.7	
Net		113.9	171.1			33.7	28.7

bay side. In other areas supratidal environment was added to the back barrier by rhizome extension coupled with gradual tidal sedimentation and by overwash. A total of 176.8 hectares was added to the back barrier (Table 48). During the past 110 years, 247.4 hectares (55 percent of the 1868 total area) has eroded from Old North Beach, but 223.9 hectares (53 percent of the 1978 area) has been added to the barrier, primarily along the bay shoreline.

Between 1886 and 1938 the Old North Beach shoreline eroded at a rate of 1.7 meters per year, and 63.8 hectares of dune-washover was lost along the oceanside (Table 49). New dunes developed on areas that had been buried by overwash deposits (50 percent).

By 1952 overwash had eliminated large sections of the dune line (23.4 hectares) and shoreline erosion continued to level dunes (37.2 hectares) at a rate of 2.7 meters per year. Dunes developed between 1938 and 1952 on washovers (25.2 hectares) and on salt marshes buried by overwash (11.7 hectares). The large washovers present in 1952 (137.3 hectares--30 percent of the total area of Old North Beach) had been partly colonized by dune vegetation by 1978; 70.5 hectares of dunes developed on these washovers. Although shoreline erosion continued at a rate of 1.3 meters per year, only 18.8 hectares of dunes was eliminated along the ocean shoreline because the dune field had been poorly developed in 1952.

Table 49. Location of areas lost or gained for salt marshes and dunes on Old North Beach.

	1868-86		1886-1938		1938-52		1952-78		1868-1978	
	(ha)	(pct)[1]	(ha)	(pct)	(ha)	(pct)	(ha)	(pct)	(ha)	(pct)
Salt marsh										
Lost to:										
Washover	15.1	33	34.1	43	20.9	57	8.4	34	78.5	43
Bay side	6.7	15	7.1	9	4.3	12	3.4	14	21.5	12
Dune	23.7	52	37.2	47	11.7	32	12.9	52	85.5	46
Terminus	0.0		0.0		0.0		0.0		0.0	
Total lost	45.5		78.4		36.9		24.7		185.5	
Gained from:										
Washover	21.3	62	21.6	49	0.0		23.9	61	66.8	51
Bay side	7.2	21	17.6	40	8.2	66	6.3	16	39.3	30
Dune	6.1	18	4.6	11	4.3	34	9.0	23	24.0	18
Terminus	0.0		0.0		0.0		0.0		0.0	
Total gained	34.6		43.8		12.5		39.2		130.1	
Net change	-10.9		-34.6		-24.4		+14.5		-35.4	
Dune										
Lost to:										
Ocean	24.3	58	63.8	74	37.2	56	18.8	53	144.1	63
Washover	2.0	5	14.8	17	23.4	35	7.2	20	47.4	21
Salt marsh	6.1	14	4.6	5	4.3	6	9.0	26	24.0	10
Bay side	9.8	23	1.6	2	1.5	2	0.2	1	13.1	10
Terminus	0.0		1.6	2	0.0		0.0		1.6	1
Total lost	42.2		86.4		66.4		35.2		230.2	
Gained from:										
Ocean and washover	11.3	32	43.2	50	25.2	68	70.5	79	150.2	61
Salt marsh	23.7	68	37.2	44	11.7	32	12.9	14	85.5	35
Bay side	0.0		5.2	6	0.1	<1	5.9	7	11.2	5
Terminus	0.0		0.0		0.0		0.0		0.0	
Total gained	35.0		85.6		37.0		89.3		246.9	
Net change	-7.2		-0.8		-29.4		+54.1		-16.7	

[1]Percentage of hectares (lost or gained).

The salt-marsh area decreased gradually between 1868 and 1952 (Table 47). Since 1952 total marsh area has increased by 12 percent; however, in 110 years the total marsh area decreased by 29 percent. Some of this decrease may be accounted for by the inability of Old North Beach to develop new salt marsh to the lee of the barrier, since 37 percent of the back barrier abuts glacial deposits (Fig. 90). Most of this marsh was lost to washovers (43 percent) and dunes that developed on the washovers.

There have been five major environments on Old North Beach in the past 110 years: dune, salt marsh, shrub, washover, and sandy beach. The only major shrub communities on the Nauset Spit system are located on Old North Beach. Shrubs were undoubtedly present on the spit before 1938, but were not indicated on the U.S. Coast and Geodetic Survey (USCGS) maps. Dunes present in 1978 along the northern section of Old North Beach were the best developed for the entire system. The dune line was continuous for up to 2000 meters, averaging 8 to 10 meters high and 200 meters wide. Salt marshes on Old North Beach were also the best developed and widest on North Beach. In one area (site of 1626 inlet) the marsh is about 1000 meters wide.

Dune area data collected from each map appear in Table 47. Dune and washover environments were not differentiated on early maps. Although the combined dune and washover area changed little between 1868 (194.3 hectares) and 1886 (191.7 hectares), 42.2 hectares eroded and 35.0 hectares of dune-washover developed in new areas. Table 49 indicates that most of this loss was caused by shoreline erosion along both the oceanside (58 percent) and along the bay shore near the spit terminus (23 percent). New dunes (and washovers) developed landward of the 1868 features, primarily on washovers (32 percent) and on salt marshes that had been buried by overwash (68 percent).

Twelve percent of the salt-marsh loss between 1868 and 1978 was attributed to bay-side erosion. Tidal currents behind Old North Beach do not generally move large volumes of sediment or erode cohesive salt-marsh peat. A total of 130.1 hectares of new salt marsh developed along the bay shore of Old North Beach between 1868 and 1978. Most of these marshes developed on old washovers (51 percent) and by rhizome extension into shallow Pleasant Bay (30 percent).

Shrub communities have rapidly expanded in the past 40 years on Old North Beach. These communities develop on supratidal substrate that is protected from salt spray behind continuous barrier dunes. A well-diversified shrub community can develop in as little as 26 years on North Beach. One washover created in 1952 supported several hectares of shrubs in 1978. Often shrubs colonize washover termini, as dune vegetation stabilizes the boundaries of the closing washover. With the termination of overwash and the development of a continuous foredune line, low-lying areas in the back barrier dunes may provide an environment for colonization by shrubs.

The Old North Beach section of Nauset Spit has not been subject to inlet dynamics within the past 110 years nor to very rapid shoreline erosion. While the barrier has eroded mainly along the ocean shore, substrate has been placed along the bay shore by overwash so that the barrier has lost little width through time. Old North Beach will continue to migrate toward the glacial deposits at Nauset Heights and at Big and Little Pochet Islands (Fig. 90), and will narrow at these locations until the moraine is subject to wave attack. Because Pleasant Bay is very shallow behind Old North Beach and the tidal

range is reduced at the head of the bay, large quantities of water do not build up behind the barrier during storms, which greatly minimizes the probability of inlet breaching. This area is also discontinuously underlain by well-developed salt-marsh peat, which prevents surges from scouring a subaqueous channel through the barrier.

e. New North Beach. The New North Beach section of the Nauset Spit system has developed since 1868 as a result of spit elongation (Fig. 3). Following the formation of the inlet through North Beach in 1846 across from Allen Point, the isolated section of the inlet began to migrate landward. In 1851 dunes and salt marshes were still prominent on this island (Fig. 106): a total of 274.6 hectares of dune-washover and 20.7 hectares of salt marsh (Table 50). The dune line along the central section does not appear to have been interrupted by any washover breaches. The average barrier width was 458 meters along the entire island and 505 meters along the central section (Table 43). The northern and southern ends of the island had begun to erode rapidly and were dominated by washovers.

All that remained of the new island by 1886 was a narrow, unvegetated supratidal sandbar (Fig. 106). As a result of a major northeaster in 1868, the inlet initiated in 1846 widened and deepened, becoming the major channel into Pleasant Bay. Sediment transported as littoral drift was cut off from the island, since the inlet intercepted or diverted eastward most of the previously available sand. The island had eroded landward an average of 795 meters in 35 years. Dunes and salt marshes were not evident on the barrier in 1886, and the average width was only 153 meters (Table 43).

As the island eroded landward between 1851 and 1886, the inlet migrated 1525 meters southward at a rate of 85 meters per year. A total of 90.7 hectares of new supratidal surface was added at the terminus of North Beach. No dunes and salt marshes had developed on this section by 1886.

The south island migrated onto the Chatham mainland during the 1890's. As the inlet continued to move southward between 1886 and 1938, an additional 3500 meters was added to the spit terminus at a rate of 67 meters per year. This lower rate of elongation was caused by the development of numerous spit recurves. Spit width and back-barrier contour on New North Beach correlate with mainland shore features, creating a roughly consistent distance between the mainland and the barrier (McClennen, 1979). It appeared that the channel between Chatham Inlet and Pleasant Bay had maintained a consistent width-to-depth ratio established by the volume of water flushing from Pleasant Bay with each tide. Opposite concavities in the Chatham coastline, spit recurves have widened the barrier (Hayes, 1981). Between 1886 and 1938 North Beach elongated opposite an embayment in the mainland at the Chatham Fish Pier (Fig. 90). In this region the barrier widened to as much as 800 meters.

In 1938 New North Beach was 4.1 kilometers long and extremely wide, averaging 626 meters (Tables 41 and 43). A total of 242.5 hectares of new supratidal environment was added at the spit terminus between 1886 and 1938 (Table 50). By 1938 broad dunes had formed on 91 hectares and salt-marsh vegetation had colonized 16.8 hectares.

Between 1938 and 1952 New North Beach rapidly extended southward as sand was added to the spit terminus across from the Chatham Light area, which arcs

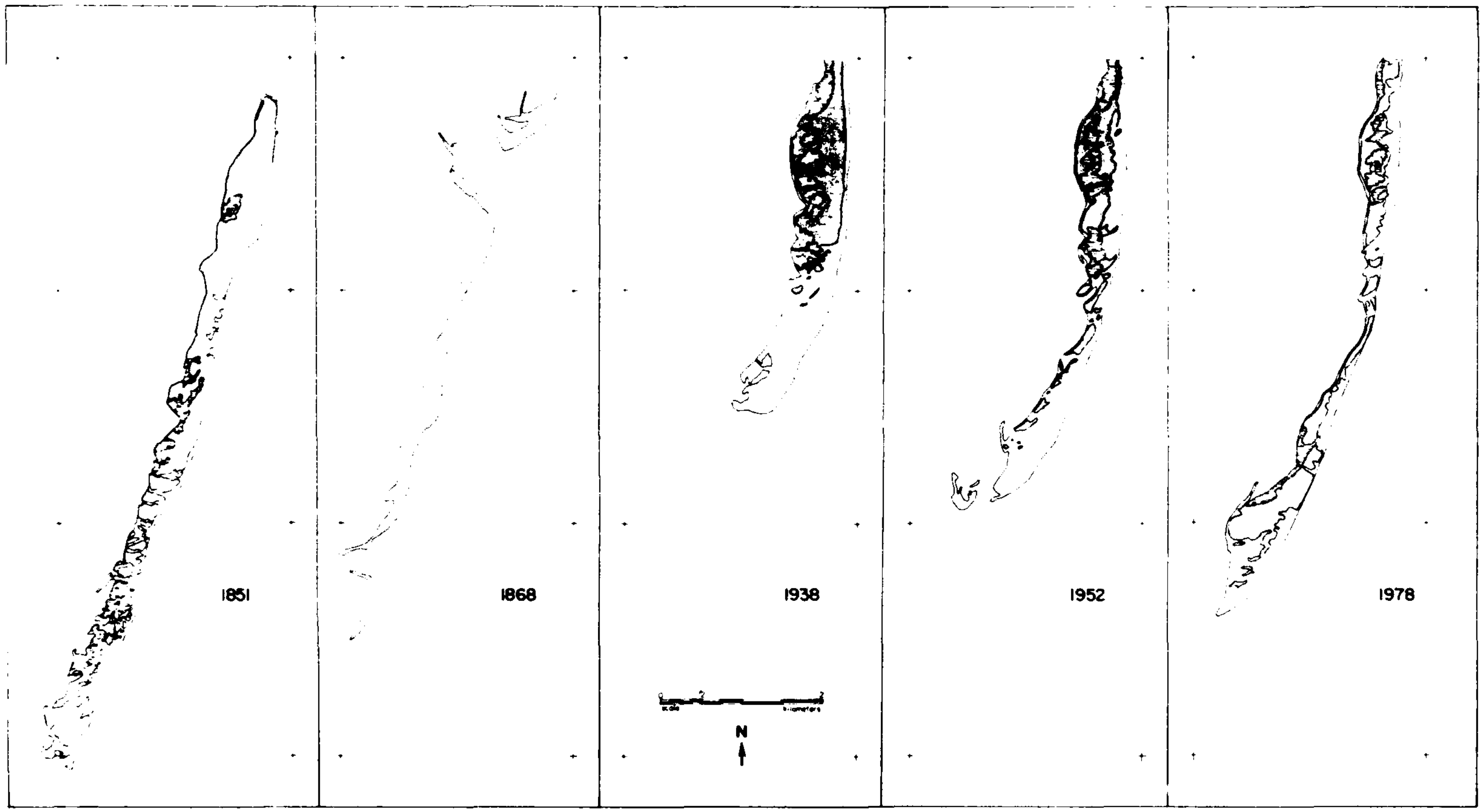


Figure 106. Evolution of New North Beach, 1851 to 1978.

Table 50. Area of barrier environments, New North Beach.

Year	Dunes (ha)	Dunes (pct)[1]	Washovers (ha)	Washovers (pct)	Marshes (ha)	Marshes (pct)	Shrubs (ha)	Sandy shorelines (ha)	Sandy shorelines (pct)	Total supratidal environments (ha)	Total supratidal environments (pct)
1851	274.6[2]		274.6[2]		20.7		0.0	85.5		380.8	
1886	0.0[2]		0.0[2]		0.0		0.0	90.7	+6	90.7	-76
1938	91.0		20.7		16.8		0.0	114.0	+26	242.5	+167
1952	71.6	-21	82.9	+300	15.0	-11	2.6	51.8	-55	223.9	-8
1978	107.1	+50	77.7	-6	14.7	-2	0.0	36.3	-30	235.8	+5
Overall change		-33[2]		-33[2]		-29			-58		-38

[1] Increase and decrease in hectares.

[2] The 1851 and 1886 maps do not differentiate dunes and washovers.

eastward; a total of 1100 meters was added to the length of the spit at a rate of 78 meters per year. The shoreline eroded very rapidly along the oceanfront of New North Beach (6.2 meters per year) during this period. Erosion also occurred along the bay shoreline, as tidal currents reworked the broad 1938 spit terminus. The barrier environment eroded 34.9 hectares along the oceanfront and 47.7 hectares along the bay side (Table 51). The average barrier width narrowed from 626 meters in 1938 to 445 meters in 1952 (Table 43).

Table 51. Location of changes in total barrier area calculated from serial map overlays, New North Beach.

Year	Bay shoreline Loss (ha)	Bay shoreline Gain (ha)	Oceanfront Loss (ha)	Oceanfront Gain (ha)	Spit terminus Loss (ha)	Spit terminus Gain (ha)
1851 to 1886	---	---	380.9	---	---	---
1886 to 1938	5.2	5.2	77.7	0.0	0.0	228.0
1938 to 1952	47.7	0.5	34.9	0.0	0.0	63.5
1952 to 1978	13.5	15.5	83.8	0.0	0.0	93.7
1851 to 1978	66.4	21.2	575.8	0.0	0.0	385.2
Net[1]	45.2		575.8			385.2

[1] Net loss for entire section, 1851 to 1978, = 235.8 hectares. Net gain for entire section, 1886 to 1978, = 145.1 hectares.

Although 1100 meters was added to the length of the spit, the total land area actually decreased by 8 percent (Table 50). The total dune area decreased by 21 percent between 1938 and 1952. Dunes on New North Beach develop and erode very rapidly. Of the 91 hectares of dunes in 1938, only 27 percent remained in 1952 (Table 52). Along the oceanside, 32.6 hectares of dunes eroded and 20.2 hectares of dunes were destroyed by overwash. New dunes (44.2 hectares) developed on washovers (46 percent) and at the spit terminus (27 percent).

Table 52. Location of areas lost or gained for salt marshes and dunes on New North Beach.

	1886-1938 (ha)	1886-1938 (pct)[1]	1938-52 (ha)	1938-52 (pct)	1952-78 (ha)	1952-78 (pct)	1868-1978 (ha)	1868-1978 (pct)
Salt marsh								
Lost to:								
Washover			1.0	16	8.0	69	9.0	50
Bay side			0.6	9	0.0		0.6	3
Dune			4.8	75	3.6	31	8.4	47
Terminus			0.0		0.0		0.0	
Total lost			6.4		11.6		18.0	
Gained from:								
Washover	1.2	7	0.0		3.9	34	5.1	14
Bay side	0.4	2	0.1	1	3.1	27	3.6	10
Dune	0.0		8.1	99	1.6	14	9.7	27
Terminus	15.2	91	0.0		2.8	25	18.0	49
Total gained	16.8		8.2		11.4		36.4	
Net change	+16.8		+1.8		-0.2		+18.4	
Dune								
Lost to:								
Oceanside			32.6	51	15.0	44	47.6	48
Washover			20.2	32	16.1	47	36.3	37
Salt marsh			8.1	13	1.6	5	9.7	10
Bay side			2.7	4	1.4	4	4.1	4
Terminus			0.0		0.0		0.0	
Total lost			63.6		34.1		97.7	
Gained from:								
Oceanside and washover	19.5	21	20.5	46	23.2	33	63.2	31
Salt marsh	0.0		4.8	11	3.6	5	8.4	4
Bay side	1.0	1	3.5	8	5.4	8	9.9	36
Terminus	70.4	77	11.9	27	37.4	54	119.7	58
Total gained	90.9		44.2		69.6		204.7	
Net change	+90.9		-19.4		+35.5		+107.0	

[1]Percentage of hectares (lost or gained).

Salt-marsh area also decreased between 1938 and 1952 (11 percent). Several new marshes developed as others were buried by washovers or eroded along the bay side. Thirty-eight percent of the 1938 salt-marsh area was lost by 1952; 55 percent of the salt marsh present in 1952 had developed over 14 years.

Between 1952 and 1978, the length of North Beach increased slowly at a rate of 54 meters per year; 1500 meters was added at the terminus. During this period, spit recurves formed opposite the embayment between Chatham Light and Morris Island and across from the breach between Morris Island and the northern end of Monomoy Island (Fig. 3). By 1978 the spit was approximately 1600 meters short of its maximum length in 1851.

An average of 5.5 meters per year was lost from New North Beach shoreline between 1952 and 1978. In one area opposite Chatham Light, the bay shoreline of 1952 was seaward of the 1978 ocean shoreline, indicating migration exceeding the 180-meter barrier width in 26 years. Overwash had widened the barrier in this very narrow region without developing an inlet. Average barrier width of New North Beach was reduced to 279 meters despite the development of a broad dune field at the southern end of the spit. A total of 83.8 hectares of supratidal barrier was lost along the ocean shoreline. Erosion also continued along the bay shoreline where 13.5 hectares was eroded (Table 51). Overwash was locally important in the maintenance of barrier width; 15.5 hectares was added to the back barrier. In one area, however, across from Chatham Light, the barrier was only 74 meters wide in 1978. If erosion rates of more than 5 meters per year continue, this area would be entirely eroded in 15 years unless overwash significantly builds new bay-shore substrate.

Although dune environment increased by 50 percent between 1952 and 1978, approximately one-half of the dunes present in 1952 had been leveled by shoreline erosion (44 percent of the dunes lost) and overwash (47 percent). New dunes developed at the spit terminus (54 percent of the new dunes) and on washovers (33 percent).

Although the total salt-marsh area decreased by only 2 percent between 1952 and 1978, much of the marsh was newly created; only 23 percent of the 1952 marsh was still present in 1978. The marsh had been destroyed by washovers (69 percent) and by dunes that had developed on washovers (31 percent). New marsh developed at the spit terminus (25 percent of new marsh), on washovers (34 percent), along the bay shoreline (27 percent), and in areas that had been mapped earlier as dunes (14 percent).

Since it began to develop in the 1860's, New North Beach has been subject to very rapid shoreline changes (Fig. 107). Between 1938 and 1978, 230 meters and 575.8 hectares of barrier environment was lost along the ocean shoreline. New North Beach also decreased in width from the bay shoreline. While the back-barrier surface increased by 21.2 hectares from overwash and tidal sedimentation, tidal currents eroded 66.4 hectares of barrier along the bay shoreline. The calculated ocean shoreline erosion rate of 5.8 meters per year between 1938 and 1978 correlates well with the 5.9 meters per year obtained by Gatto (1979).

As the spit increased in length, it decreased in width. The ratio of width to length was calculated for New North Beach for each set of maps (Table 53). Width-to-length ratio may be of value to predict susceptibility

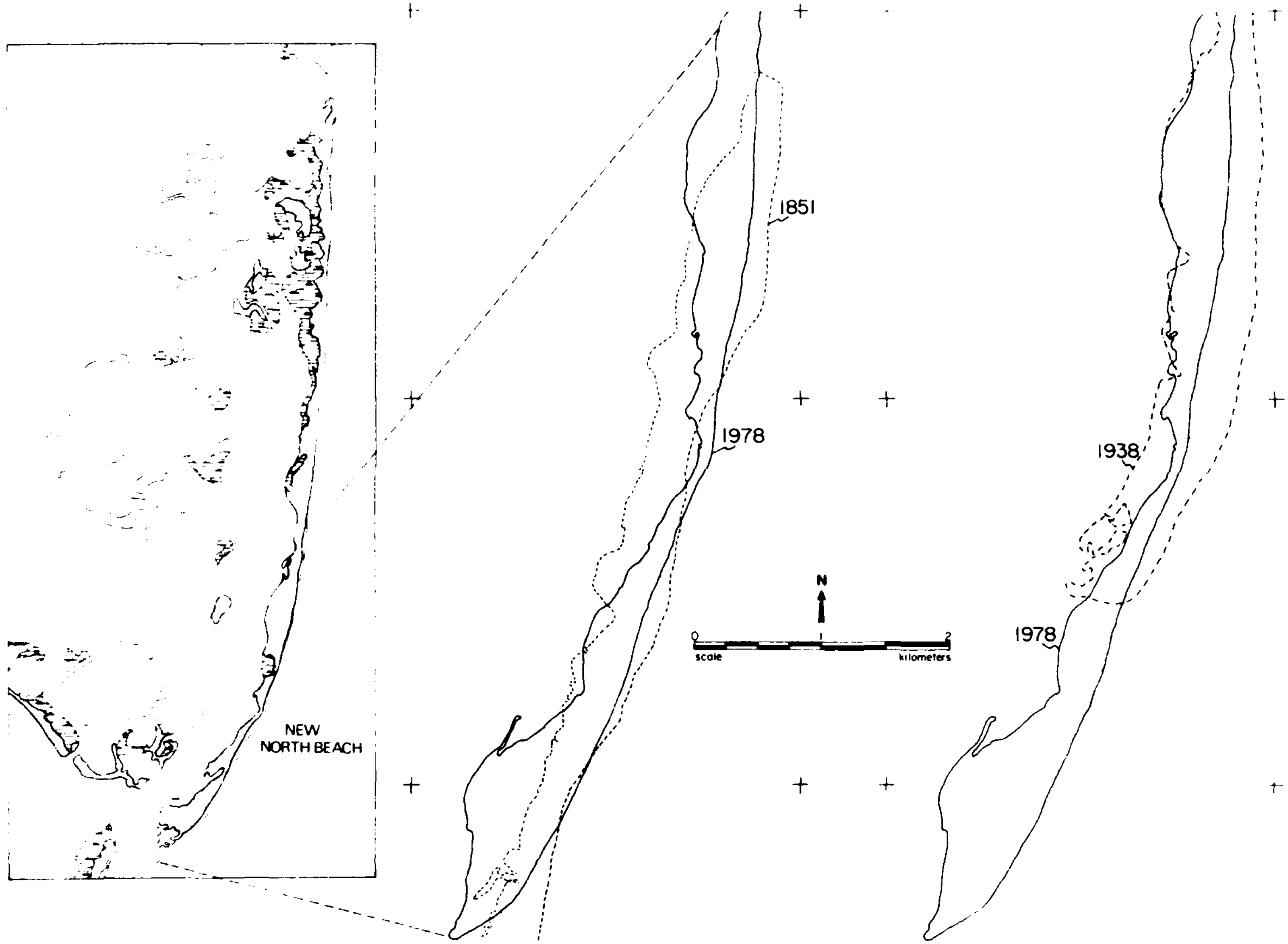


Fig. 107. Shoreline changes of New North Beach, 1851 to 1978.

Table 53. Ratio of width to length of New North Beach.

Year	Avg. width (m)	Length (m)	Width/length (m)
1851	505	8500	0.06
1886	153	6700	0.02
1938	626	4100	0.15
1952	445	5200	0.09
1978	279	6700	0.04

of the barrier to overwash breaching and inlet formation. In 1851, just after the 1846 inlet had created the island at the southern end of the spit system, the New North Beach section had a width-to-length ratio of 0.06; this ratio decreased to only 0.02 in 1886 as the spit remnants migrated landward. During early development of New North Beach, the ratio was quite high (0.15) because the spit recurves, prominent at the southern end, were very broad. Since 1938 this ratio has decreased. By 1978 the ratio (0.04) was less than it had been after the last inlet formed. The decrease in width-to-length ratio suggests that although New North Beach in 1978 was not as long as it had been in 1851, it was more vulnerable to inlet breaching.

Overwash has been locally important in increasing barrier width and shifting landward the position of dunes and salt marshes. Unlike Old North Beach, New North Beach has not, however, migrated westward by means of overwash. The distance between the Chatham mainland and the back barrier has remained fairly consistent in the last 40 years. New North Beach is very narrow and salt marshes have not developed substantial peat deposits. If an inlet were to form through New North Beach, the barrier would very quickly erode landward.

5. Vegetative-Physiographic Transects.

a. Introduction. Field research was conducted on North Beach and Nauset Spit-Orleans during 1978 to determine the successive sequence of plant communities that develop on washovers and to characterize physiographic features resulting from washover stabilization, inlet dynamics, and plant community development. Fifteen areas were chosen for study: eight were located on Old North Beach, five on New North Beach, and two on Nauset Spit-Orleans (Fig. 90). These areas were selected on the basis of overwash history, vegetative characteristics, and present physiographic features. An attempt was made to include all the various plant communities and physiographic features present on Nauset Spit.

b. Methodology. At each site, an elevation transect was established perpendicular to the beach (Fig. 108). Stakes were used to mark these transects for future use. Elevation readings were taken using a surveyor's level at 10-meter intervals and at points of significant topographic change.

A vegetation sampling program was conducted during late July and August 1978. Belt transects 30 meters wide were established, centered along each of the 15 elevation transects in order to sample large, representative areas (Fig. 108). At a 10-meter interval, 30-meter-long transects were constructed

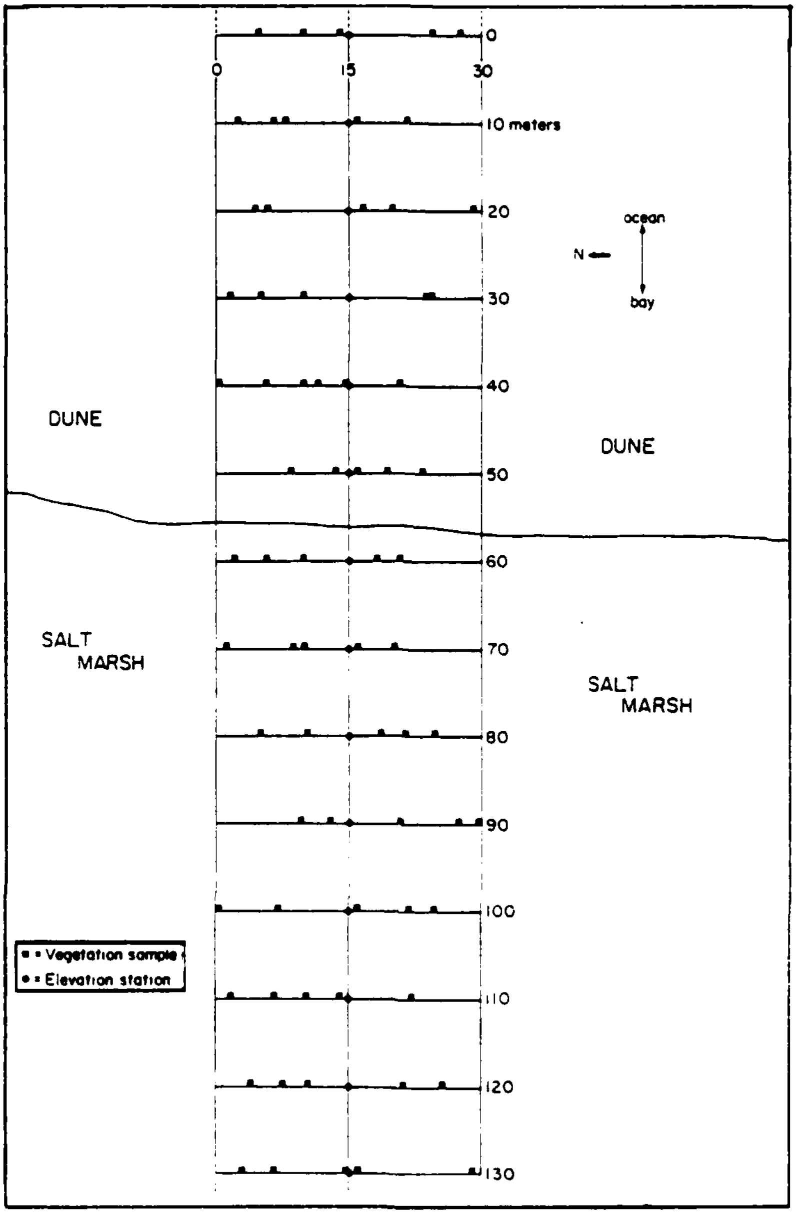


Figure 108. Example of sampling scheme for a belt transect.

perpendicular to the elevation transects. Locations of vegetation sampling stations along these transects were selected at random and recorded so that future changes could be accurately monitored. An adequate sample number per transect was determined using species-area curves (Oosting, 1956). Samples were collected until an additional sample per transect did not increase the species encountered by more than 10 percent. Five samples were taken along each 30-meter transect.

Vegetation information was collected for herbaceous plants using a standard 25-hole, 0.25-square meter point-intercept board (Oosting, 1956). Data concerning presence and cover of plant species were recorded. For shrub communities, nested quadrats were used, and a 4- by 4-meter quadrat

was used for high vegetation. Cover data were collected using cover classes (Daubenmire, 1968). The 0.25-square meter point-intercept board was used for lower vegetation.

Species lists and community distinctions were made for each belt during fieldwork. Biomass data were collected in typically healthy and senescent stands of *Ammophila breviligulata* at each belt using a buoyancy board (Woodhouse and Hanes, 1976). Ten samples were selected at random within each stand. The buoyancy board has been calibrated for *Ammophila breviligulata* on Cape Cod (Brodhead and Godfrey, 1979; Fig. 109). Vegetation data were compiled and are presented as bar graphs associated with an elevation transect.

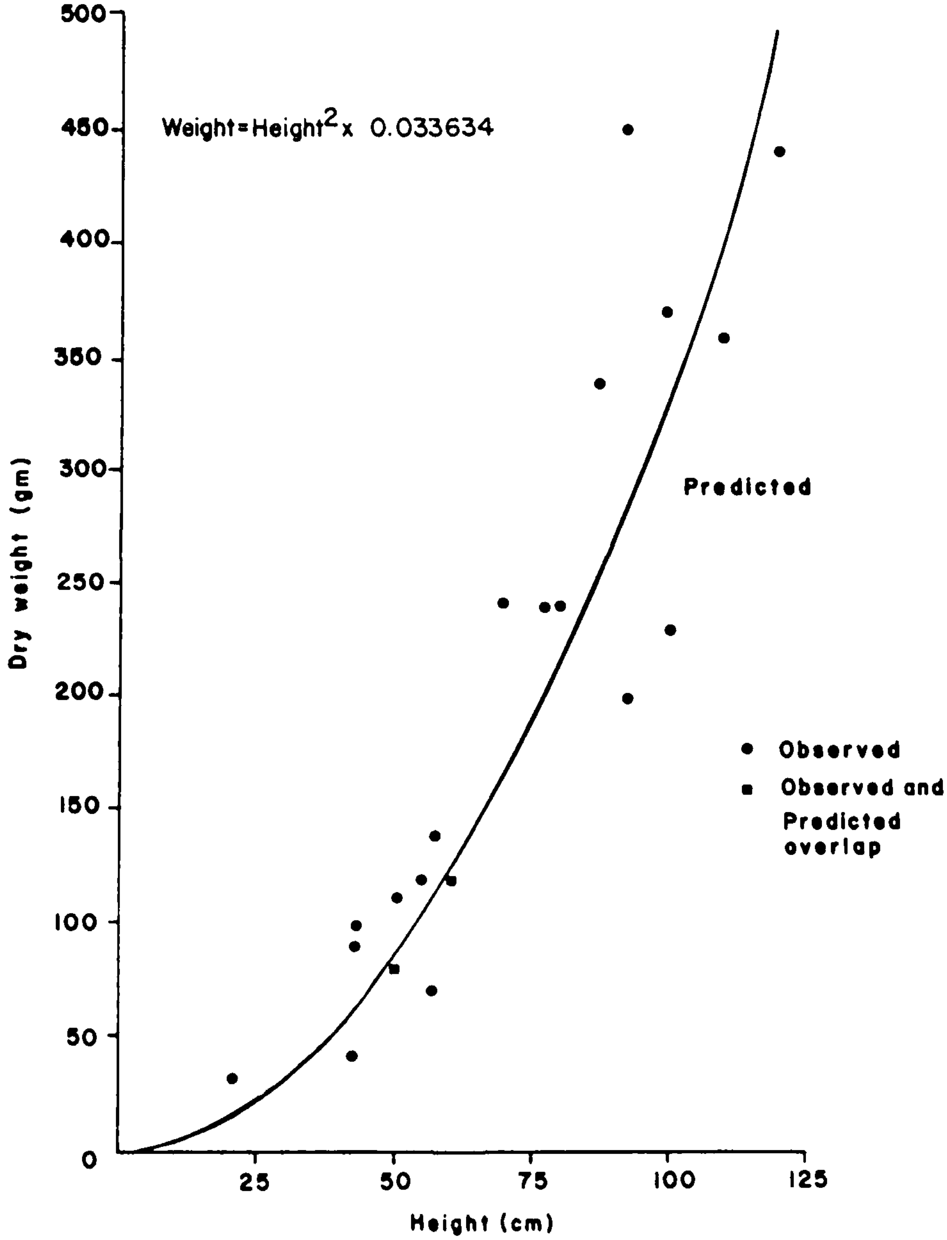


Figure 109. Buoyancy board calibration curve for *Ammophila breviligulata* (from Brodhead and Godfrey, 1979).

c. <u>Belt Histories and Descriptions</u>. Six sites were chosen on Old North Beach that have, in large part, not been affected by overwash recently. These belts (A, B, C, E, F, and Z) will be discussed first, followed by those areas which were recently created.

Belt A is located 1000 meters south of the Orleans parking lot (Fig. 90). In 1868 this belt consisted of a continuous dune line backed by a broad salt marsh (360 meters) abutting the glacial moraine (Fig. 110). Between 1886 and 1938, overwash occurred along the spit for about 1000 meters on either side of belt A. The dunes were completely leveled, and a new, continuous dune line had developed by 1938 on what had been salt marsh. Although this dune line was disturbed again by overwash prior to 1952, sand was transported only part of the distance across the barrier. Remnants of the dune line had expanded and coalesced, reestablishing a continuous dune line by 1978. In 1978 belt A consisted of a dune line 130 meters broad and 10 meters high which was backed by a shrub community and a *Spartina patens-Agropyron pungens* grassland and marsh (Fig. 111).

In the past 110 years, 183 meters of the belt A shoreline has eroded. Overwash has driven the barrier dunes westward over the salt marsh. Unable to expand landward, the salt marsh has become progressively narrower (Table 54). The landward part of this belt is, therefore, older than 110 years, whereas parts of the dune line have developed since 1952.

Belt B is located 1000 meters south of belt A (Figs. 90 and 110). In 1868 this belt consisted of a narrow dune line fronting a broad salt marsh. The dunes at belt B were leveled by overwash prior to 1886, and washover flats extended beyond the back-barrier shoreline into the bay. By 1886 the bayward margin of the belt had been recolonized by salt-marsh vegetation. Overwash must have continued at belt B during this period, since by 1938 the back barrier shoreline had extended about 75 meters farther into the western creek and dunes had developed on the recently established salt marsh.

Between 1938 and 1978, few major changes occurred at belt B. Shoreline erosion reduced the barrier width and dune line by about 40 meters. The dune line was 200 meters broad and 8 to 10 meters high in 1978 (Fig. 112). Along 70 meters of the dune line a well-developed, stable dune-heath community was present, dominated by *Hudsonia tomentosa* (false beach heather). As at belt A, a grassland community graded into a broad *Spartina patens* marsh. *Spartina alterniflora* grew only at the creek margin.

Belt C is located 1000 meters south of belt B and because it is backed by Pochet Island, it no longer migrates landward (Fig. 90). In 1868 belt C consisted of a narrow dune line backed by a narrow marsh, a broad creek, a second broad marsh, and a creek (Fig. 110). Prior to 1886 this belt overwashed, filling the broad creek and extending the barrier to the base of the glacial cliff at Pochet Island. A massive washover must have extended at least 375 meters landward of the berm crest. By 1886 dunes had developed at the back of the washover which was still barren along the seaward edge. Dunes present in 1886 were all landward of the 1868 dune line.

Between 1938 and 1978 very few changes occurred at belt C. Although the barrier narrowed during this period, the dune line expanded landward and increased in width, probably because the creek at the base of Pochet Island

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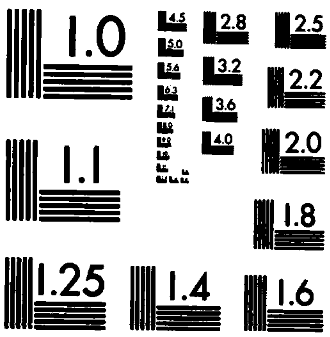

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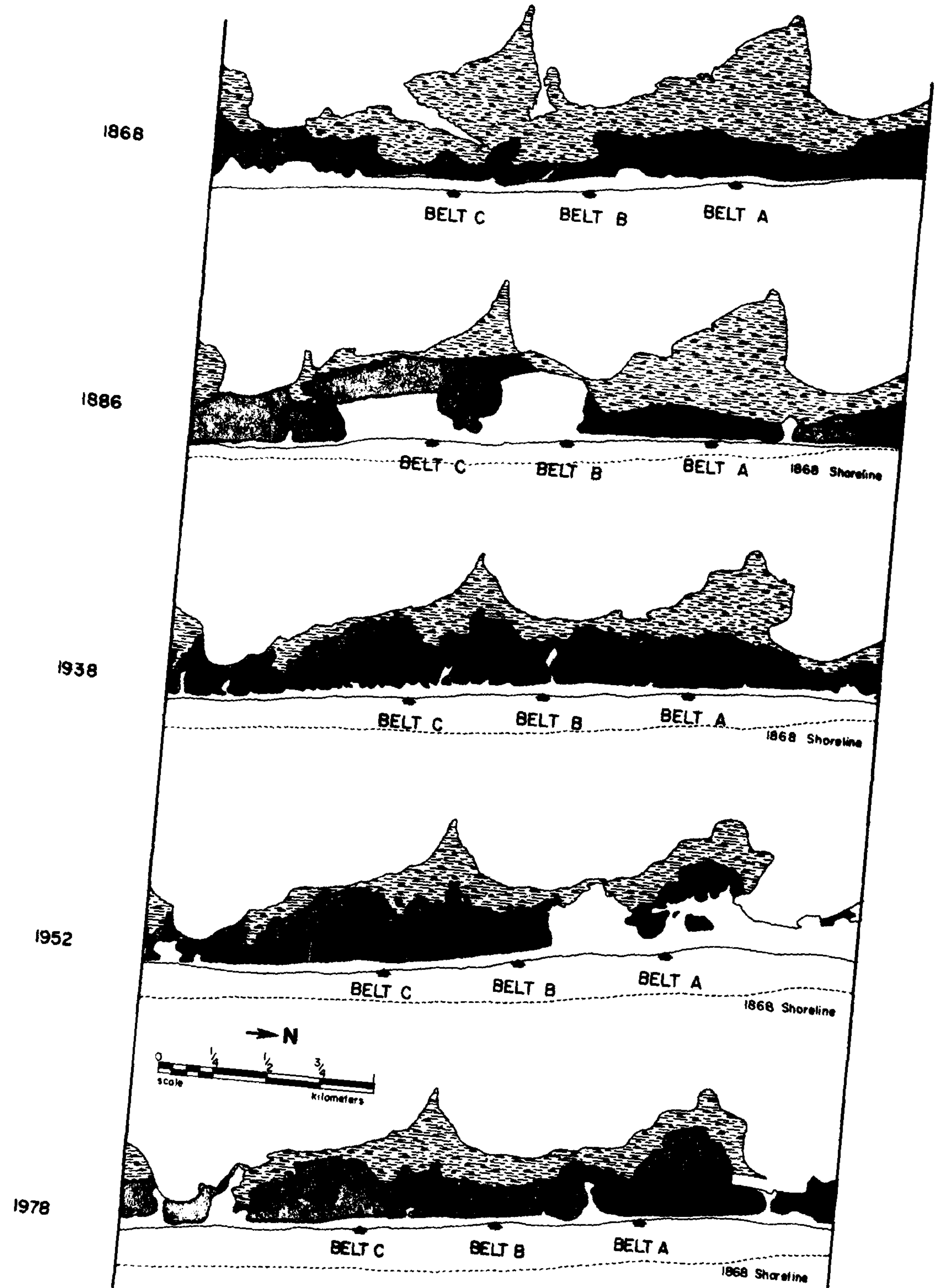

Figure 110. Historic maps of belts A, B, and C.

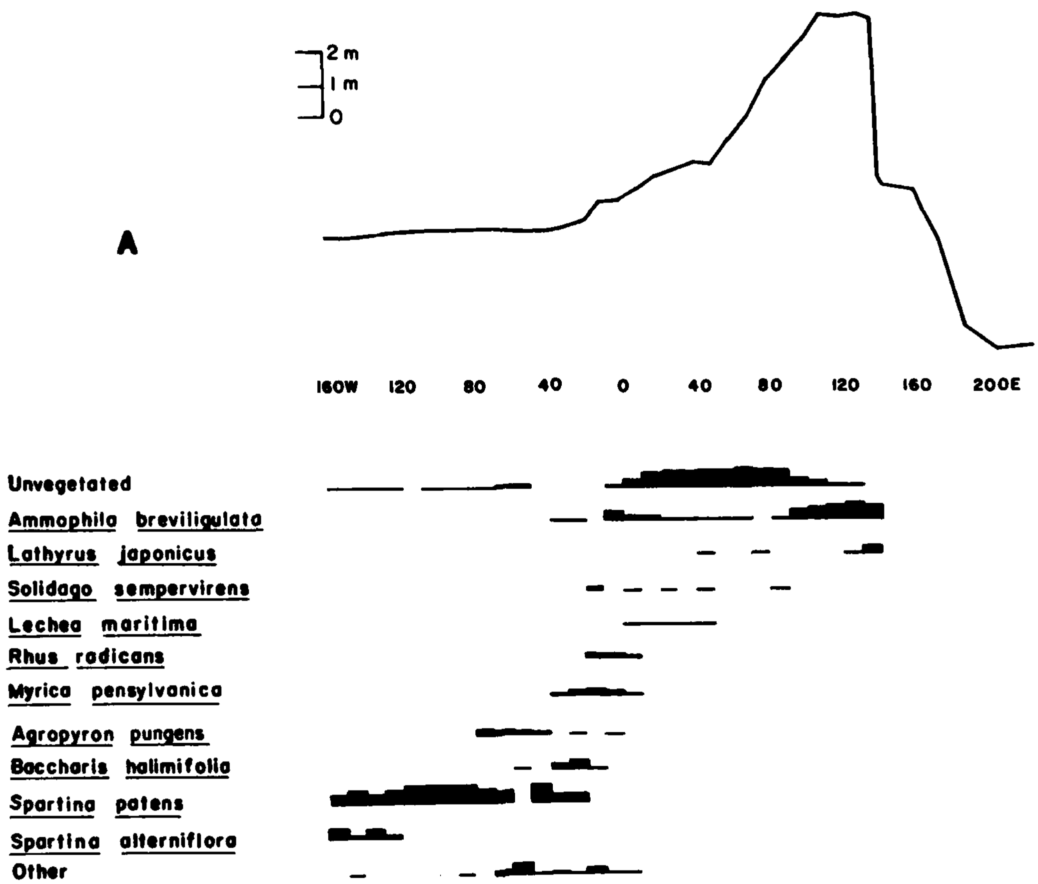

Figure 111. Vegetative-physiographic transect of belt A.

Table 54. Barrier widths at 15 belt sites.

Belt	1868 (m)	1886 (m)	1938 (m)	1952 (m)	1978 (m)
A	580	570	470	430	420
B	400	350	350	340	310
C	580	440	410	440	390
D	760	820	750	810	790
E	210	530	520	560	550
F	430	380	290	300	240
G	290	210	280	610	560
H	---	110	540	410	310
I	---	---	680	520	310
J	---	---	620	240	210
K	---	---	---	650	390
L	---	---	---	---	460
X	---	---	---	---	160
Y	---	---	---	---	120
Z	310	450	290	240	240

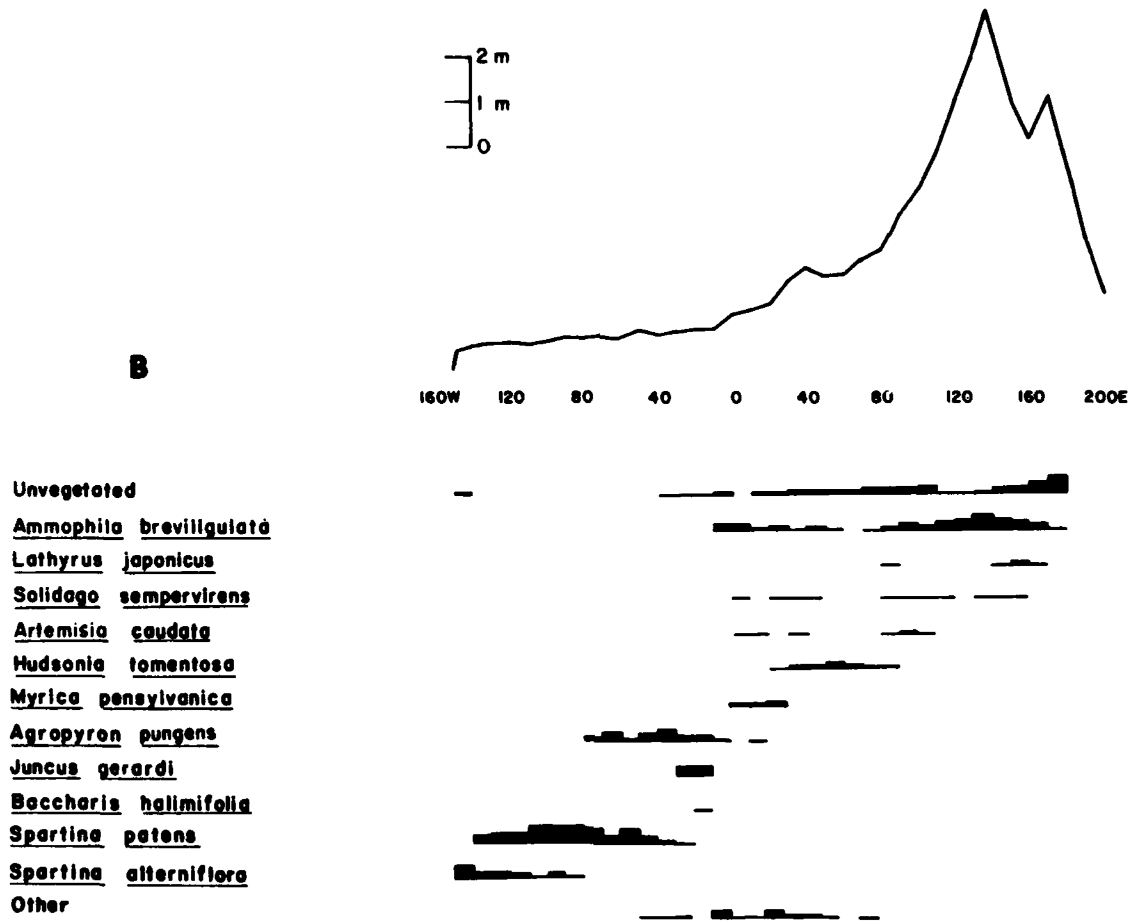

Figure 112. Vegetative-physiographic transect of belt B.

was infrequently flooded by tides and supratidal vegetation had been able to expand onto the salt marsh. In 1978 *Spartina patens* occupied only a narrow band 50 meters wide at the back of the barrier; *Spartina alterniflora* was not present at belt C (Fig. 113). The *Ammophila breviligulata* dunes were 9.5 meters high and 110 meters broad. The center 100 meters of the belt was occupied by a well-developed dune-heath community dominated by *Hudsonia tomentosa*, *Cladonia* spp., and declining and dying *Ammophila breviligulata*.

Belt E is located at a wide section of Old North Beach in the approximate location of the 1626 inlet (Fig. 90). In 1868 a washover was evident, backed by a continuous dune line and a broad creek with salt marsh to the west (Fig. 114). Between 1868 and 1886 the area was overwashed, filling the creek and extending the subaerial barrier about 335 meters landward. Dune and salt-marsh vegetation covered this washover by 1886.

Although the dune line at belt E has not been disturbed by overwash since 1886, the salt marsh has been affected by overwash several times. In 1938 belt E consisted of a continuous dune line backed by a washover deposit on part of the marsh. This washover, which crossed the dune line north of belt E, must have occurred first prior to 1938, since dunes were already evident at its outer margin, and scattered dune remnants probably would not have remained.

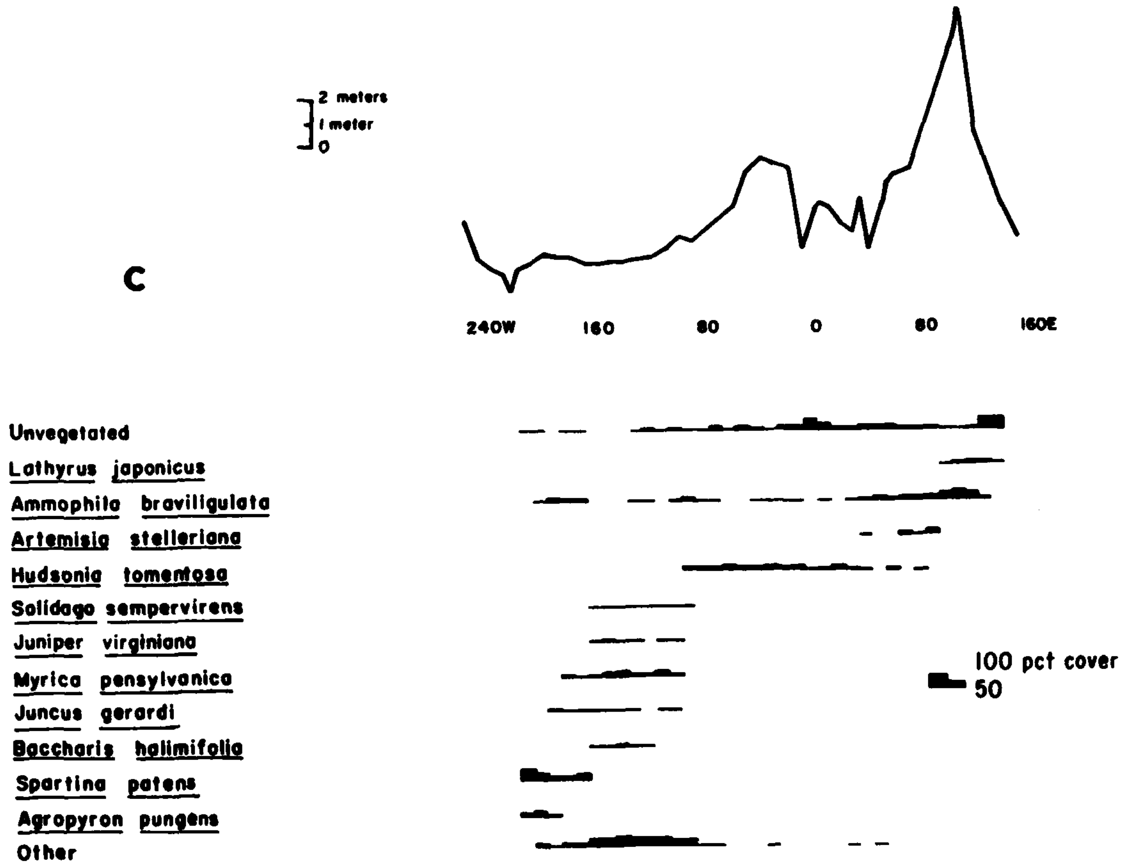

Figure 113. Vegetative-physiographic transect of belt C.

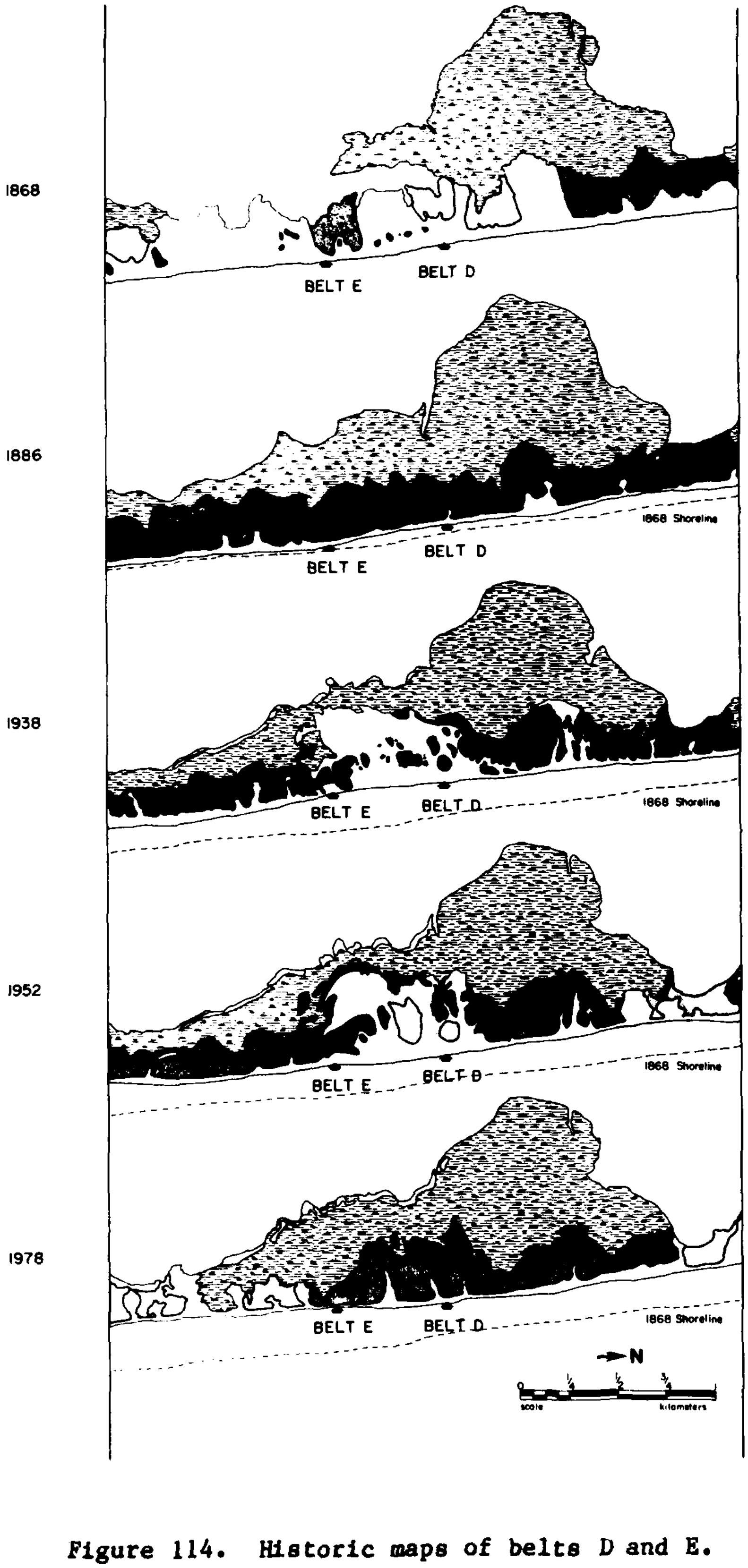

Figure 114. Historic maps of belts D and E.

Overwash continued north of belt E for many years. The washover flats were still open in 1952. Small dunes developed at the outer washover edge, and the dune line at belt E expanded landward. These dunes were not visible, however, in the 1978 imagery, and salt-marsh vegetation colonized most of the washover flats. Remnants of the dunes at the washover margin were evident from field studies (Fig. 115). A low back-dune ridge, 80 centimeters high, crossed belt E and was dominated by dead and dying *Ammophila breviligulata*, *Agropyron pungens*, and *Spartina patens*. The back dunes present in 1938 and 1952 were only marginally supratidal. After continuous dunes north of belt E had developed and washover sand supply to the back barrier was cut off, these marginal dunes deflated to an elevation where *Spartina patens* could grow. In 1978 the dune line was 7 meters high and 160 meters broad; the salt marsh was very wide with broad bands of both *Spartina patens* and *Spartina alterniflora*. The dunes at belt E are more than 40 years old; the eastern part of the salt marsh is very young--less than 26 years; and the outer edge of the marsh is at least 92 years old.

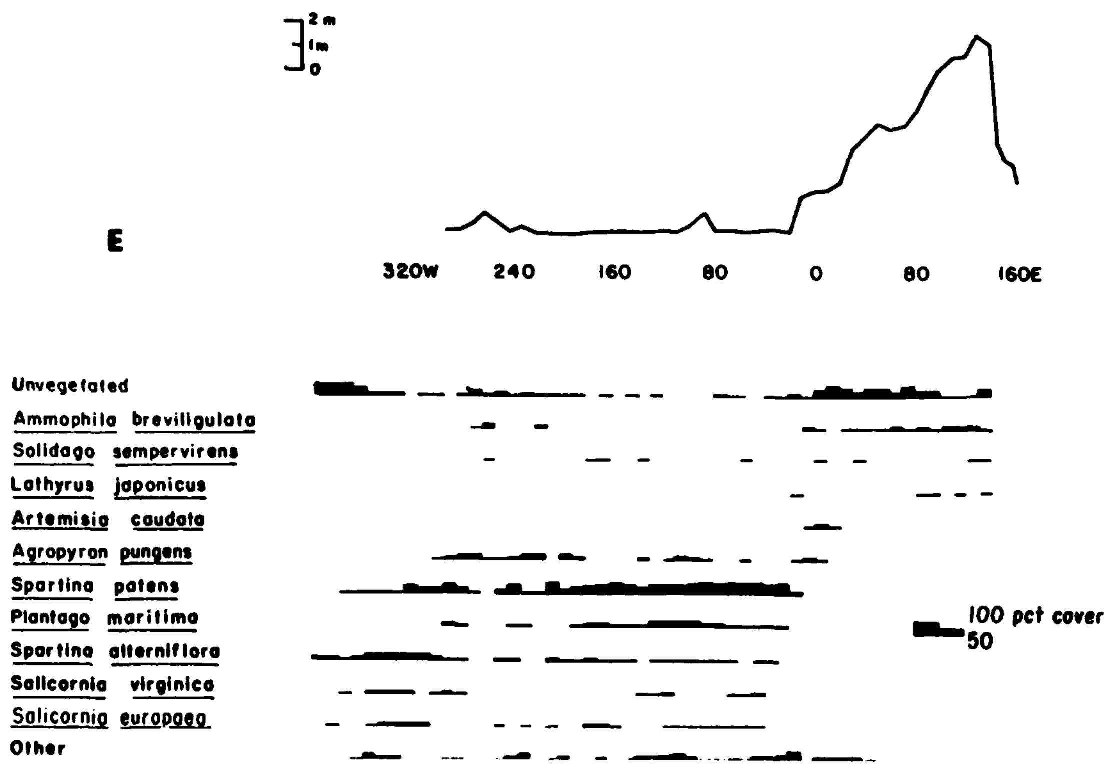

Figure 115. Vegetative-physiographic transect of belt E.

Belt F is located 1500 meters south of belt E in an area that has been stable since 1868 (Fig. 90). In 1868 the belt consisted of a recent washover which had not penetrated the back of the dune line, a narrow dune zone, and a broad salt marsh (Fig. 116). Only minor changes occurred along the belt between 1868 and 1978, apart from erosion of approximately 190 meters of the oceanside dune line (Table 54). In 1938 a narrow washover breach disturbed the oceanfront of the dune line at belt F. Massive washovers, which occurred north and south of the belt in 1938 and 1952, deflated, adding sediment to the back of the dune line. Redistribution of washover sand along the bay shore also added sediment to the bayward edge of the salt marsh.

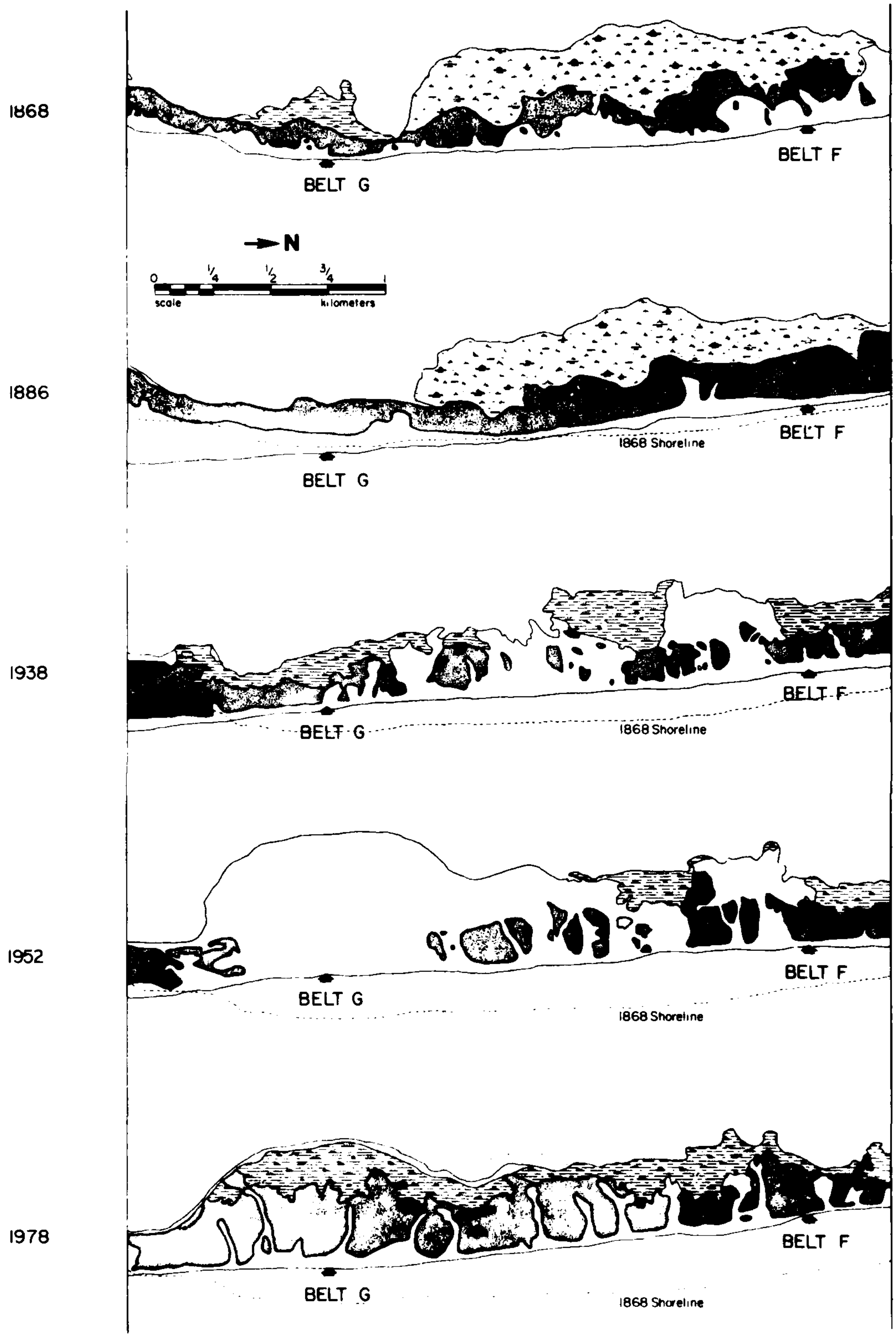

Figure 116. Historic maps of belts F and G.

In 1978 the dune line at belt F was 140 meters wide and 5 meters high (Fig. 117). Small areas of senescent *Ammophila breviligulata* with *Chrysopsis falcata* (sickle-leaved aster) and *Artemisia caudata* were located behind the foredunes. The salt marsh was broad and clearly divided into high and low marsh.

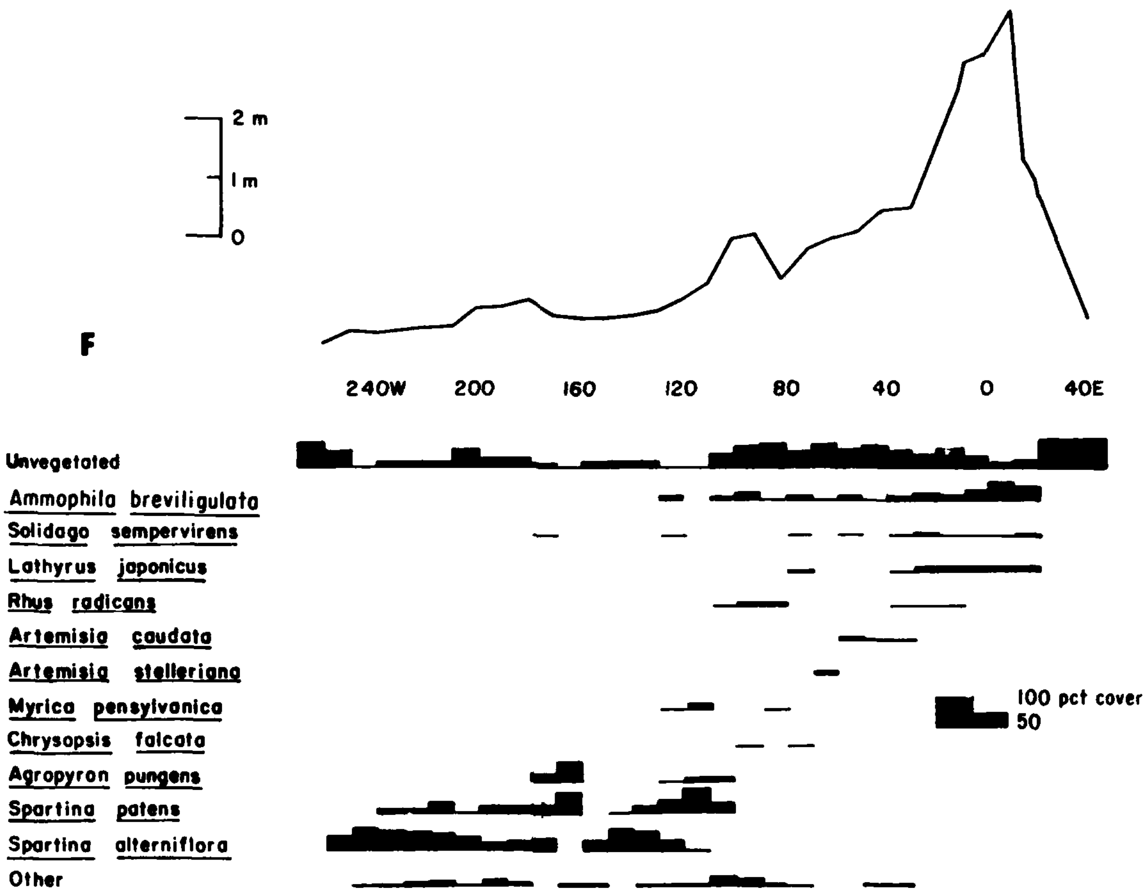

Figure 117. Vegetative-physiographic transect of belt F.

Belt Z, located below Nauset Heights north of the Orleans parking lot, crosses a brackish pond that is the last remnant of the waterway that connected Pleasant Bay to Nauset Harbor until the mid-19th century (Figs. 90 and 97). In 1868 and 1886 the pond was evident on maps and undoubtedly affected by overwash, since barrier dunes were not present (Fig. 118). Between the pond and the glacial headlands (Nauset Heights), a narrow salt marsh existed in 1868. This marsh had been filled by 1886. A broad dune line backed by shrubs lining the pond margins was evident in the 1938 imagery. No significant changes occurred between 1938 and 1978.

In 1978 a narrow but high (5 meters) dune line separated the pond from the ocean (Fig. 119). Small stands of *Spartina patens*, remnants of the earlier salt marsh, lined the eastern pond margin except where shrubs were present. *Typha latifolia* (cattail) had filled much of the pond. Below Nauset Heights the dune community was sparsely vegetated and dominated by *Artemisia caudata* and *Ammophila breviligulata*.

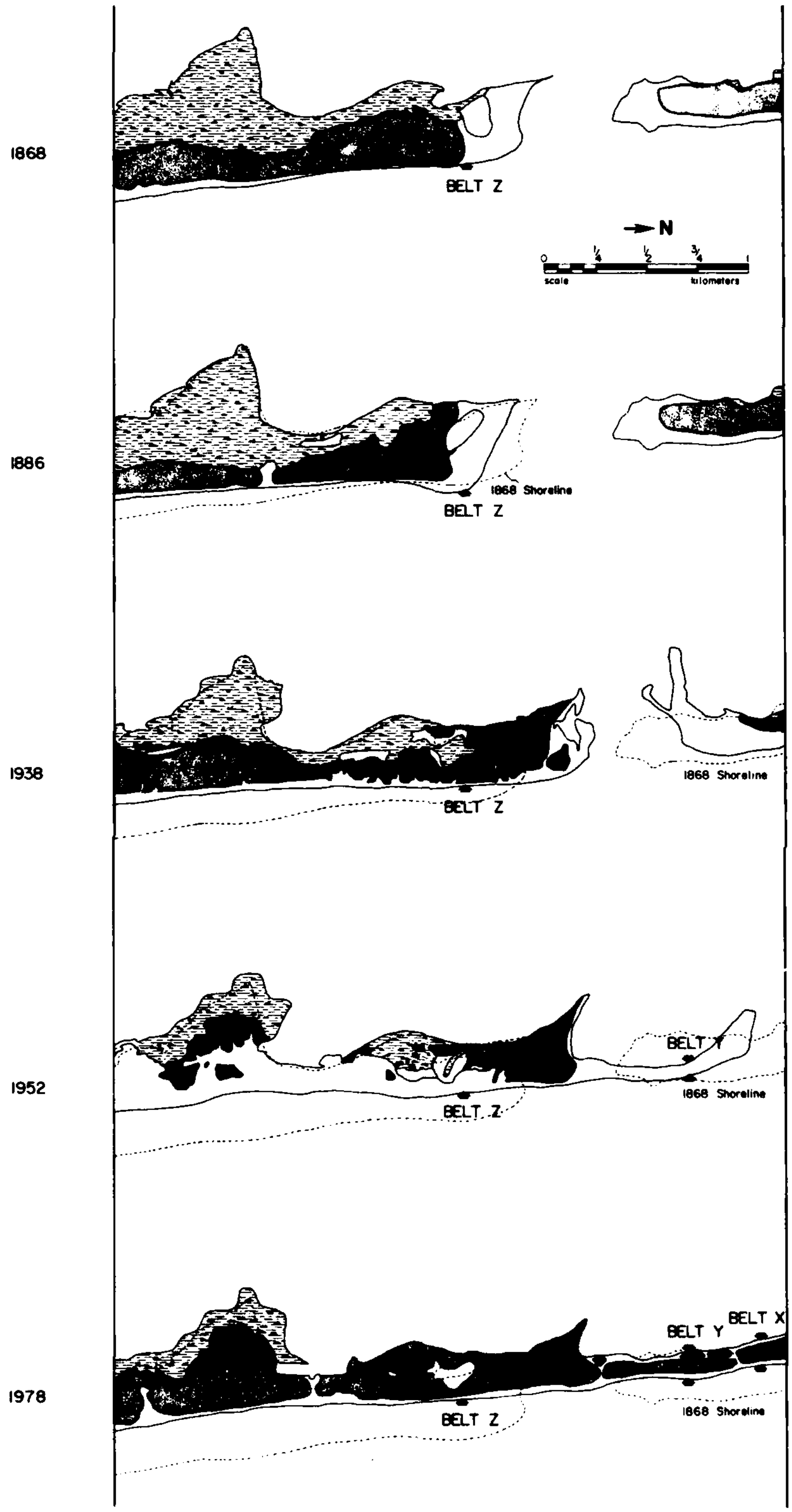

Figure 118. Historic maps of belts X, Y, and Z.

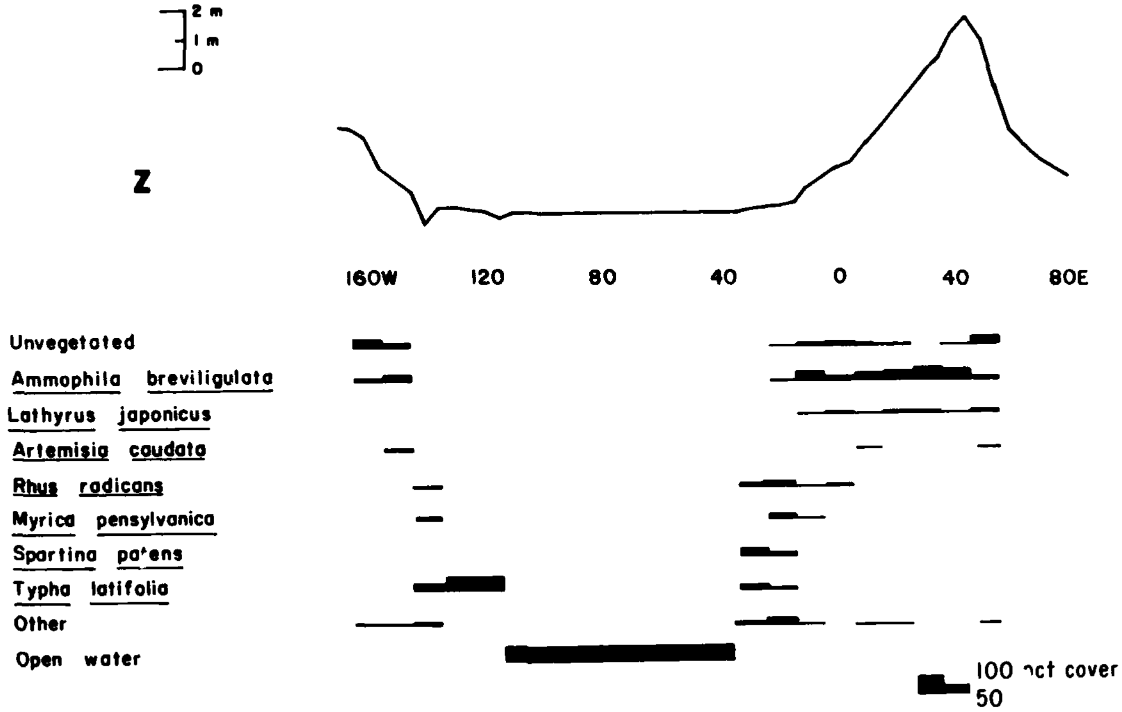

Figure 119. Vegetative-physiographic transect of belt Z.

Three areas were chosen that were either established between 1886 and 1938 (belts H and I) or were severely overwashed during the 1938 hurricane (belt D). All three of these areas are, therefore, between 40 and 80 years old.

Belt H is located approximately at the site of the 1868 inlet (Fig. 90). By 1886 the southern end of North Beach had extended as far as belt H, and was characterized by washovers at the spit terminus (Fig. 120). In 1893 Old Harbor Coast Guard Station was erected at this site, 330 meters from the ocean beach (Smith, 1909). Belt H was 8 kilometers from the spit terminus by 1938 and consisted of several dune ridges, which were remnants of spit recurves, and a salt marsh which had developed between these dunes. Between 1938 and 1952 the ocean shoreline eroded at a rate of 6.7 meters per year, reducing the dune field substantially. During this period, overwash from areas north of belt H filled most of the salt marsh in the interior without destroying the low, seaward dune line. By 1978 Old Harbor Station had been partially undermined and had to be removed by using a crane and barge. During the 1978 northeaster, overwash eroded sections of the remaining dune line burying the remnants. The features at belt H are, therefore, not all the same age. The salt marsh and back barrier spit recurve are between 40 and 80 years old, while healthy foredunes are the result of sheet washovers in 1978 on top of low dunes (Fig. 121).

Belt I, located 1000 meters south of belt H, first developed several years after the Old Harbor Station was built in 1893 (Fig. 90). As at belt H, this area, consisting of several dune ridges that were remnants of spit recurves, was very broad (677 meters) when it first formed (Fig. 120). A salt marsh, connected to the bay at high tides by a tidal creek, developed between these dunes.

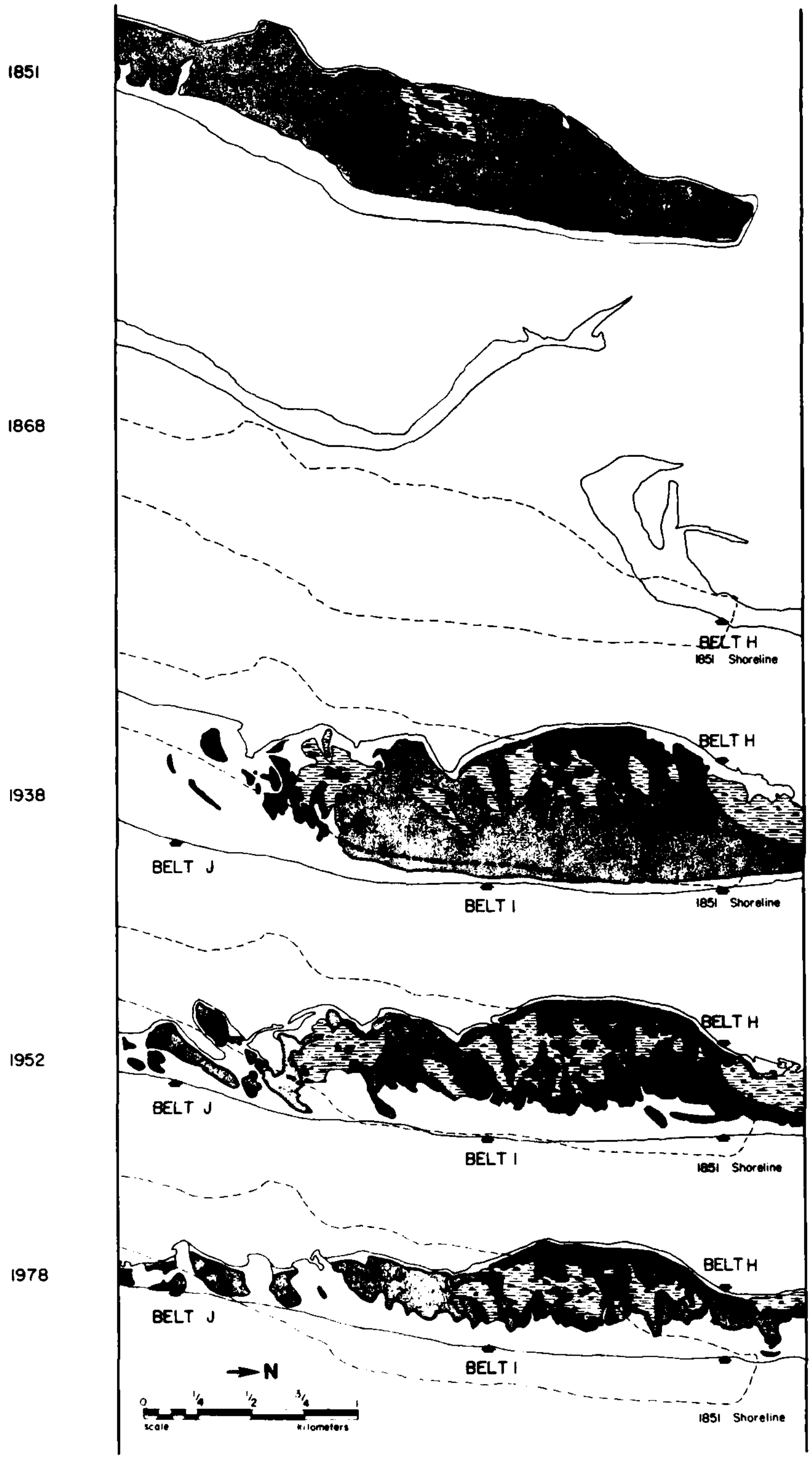

Figure 120. Historic maps of belts H, I, and J.

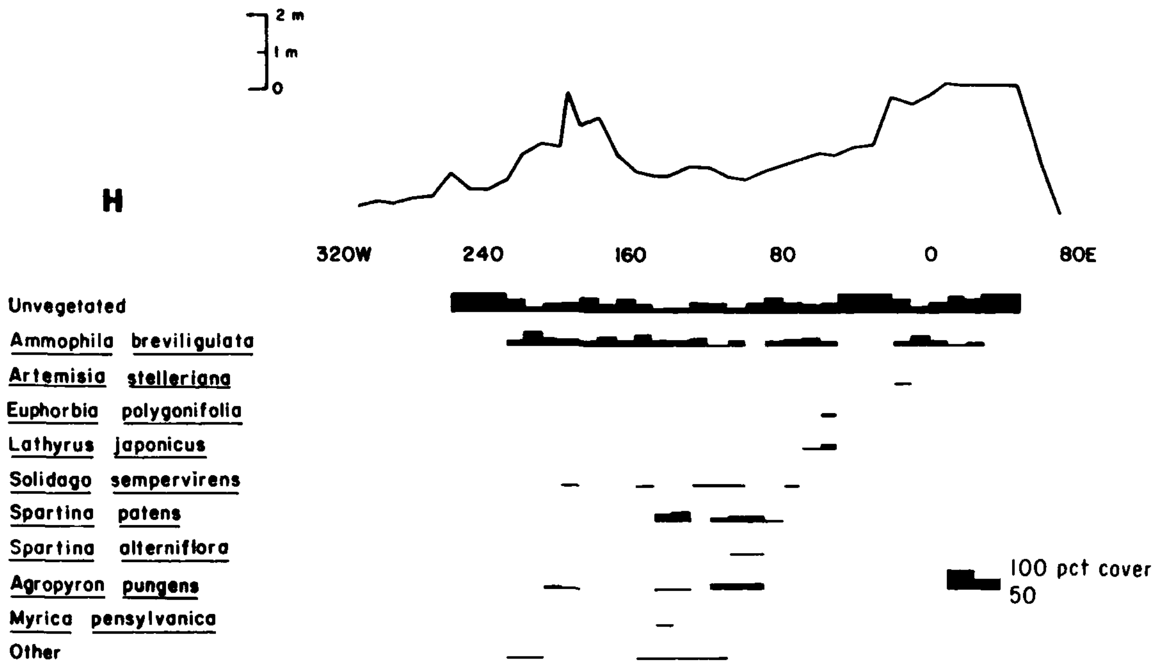

Figure 121. Vegetative-physiographic transect of belt H.

Belt I has eroded rapidly along the oceanfront, averaging 6.7 meters per year between 1938 and 1978 (Table 54). This belt was reduced to less than one-half its original width (1938) by 1978. Two spit recurve remnants were still evident in the area in 1978 (Fig. 122). The ocean dune line, approximately 2.5 meters high and 80 meters wide, was affected by sheet overwash during the 1978 storm. *Ammophila breviligulata* biomass on these dunes was the second highest measured on the Nauset Spit system (Table 55). The back-barrier ridge, 2 meters high and 80 meters wide, was no longer accreting. *Artemisia caudata* had invaded declining stands of *Ammophila breviligulata*. A broad shrub zone backed by a *Spartina patens* grassland and a small intertidal pond were located in the center of the barrier. The seaward dunes at belt I were very young, having been recently overwashed; the remainder of the belt was between 40 and 80 years old.

Belt D is located about 2 kilometers north of belt E in a very wide section of Old North Beach (Fig. 90). In 1868 the dunes at belt D were badly dissected by washovers, but there is no evidence that washover sediment was added to the marsh surface (Fig. 114). Only a small breach in the dune line was apparent by 1886.

Aerial photos taken in 1938 show that belt D was part of a massive washover that must have first occurred at least several years prior to this time. Dunes were present at the bayward edge of the washover on substrate that had been mapped as salt marsh in 1886. The isolated dunes in the interior of the washover may have been either remnant dunes present before the washover or new dunes that developed from drift piles.

Overwash continued at belt D in 1952. Several lobes of a massive washover had expanded farther onto the salt-marsh surface, but did not reach the bay because the barrier at this location was very wide. The remnant dunes expanded, reducing the washover area.

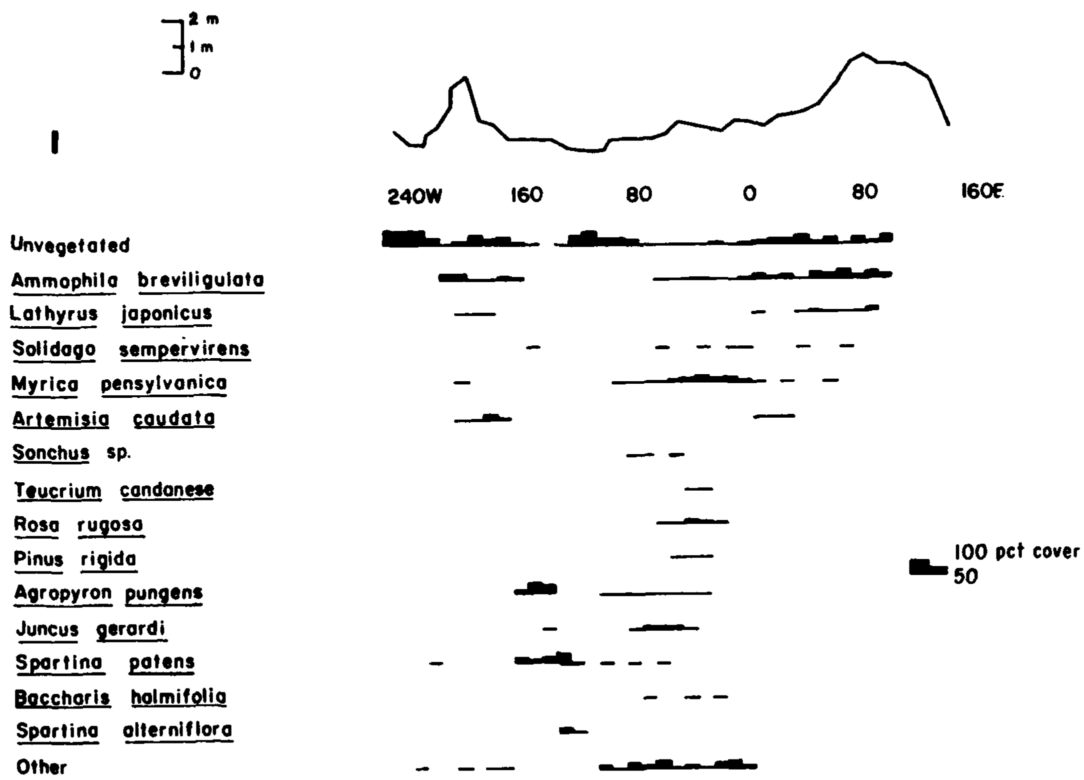

Figure 122. Vegetative-physiographic transect of belt I.

Table 55. Buoyancy board-biomass data for North Beach belt sites.

Belt	Uniform area		Biomass area			
			High		Low	
	(cm)	(g/m^2)	(cm)	(g/m^2)	(cm)	(g/m^2)
A	---	---	130.0	570	45.0	70
B	---	---	101.6	350	40.6	50
C	---	---	111.0	410	57.6	110
D	---	---	130.0	570	25.8	20
E	---	---	99.0	330	58.6	120
F	---	---	112.2	420	65.8	150
G	---	---	103.8	360	37.0	50
H	115.4	450	---	---	---	---
I	137.8	640	---	---	---	---
J	145.2	710	---	---	---	---
K	124.6	520	---	---	---	---
L	79.8	210	---	---	---	---
X	92.8	290	205.0	1410	40.6	50
Y	---	---	91.8	650	53.2	100
Z	---	---	105.2	370	72.0	170
Washover edge			160.6	870		

By 1978 a continuous dune line was present at belt D. Dunes and a shrub community had developed on the old salt marsh. The foredunes were 6 meters high but only 80 meters wide, although almost no erosion occurred at belt D between 1938 and 1952 (Fig. 123). An inspection of the topography at this belt revealed that the shrub community grew within a very narrow elevation range between marsh and dune communities. Washover deposition at the bayward edge raised the elevation to above high marsh elevations. At the dune-shrub interface, shrubs grew at the lower elevations, particularly in old washover breaches that had overwashed most recently and were at a slightly lower elevation than surrounding dunes.

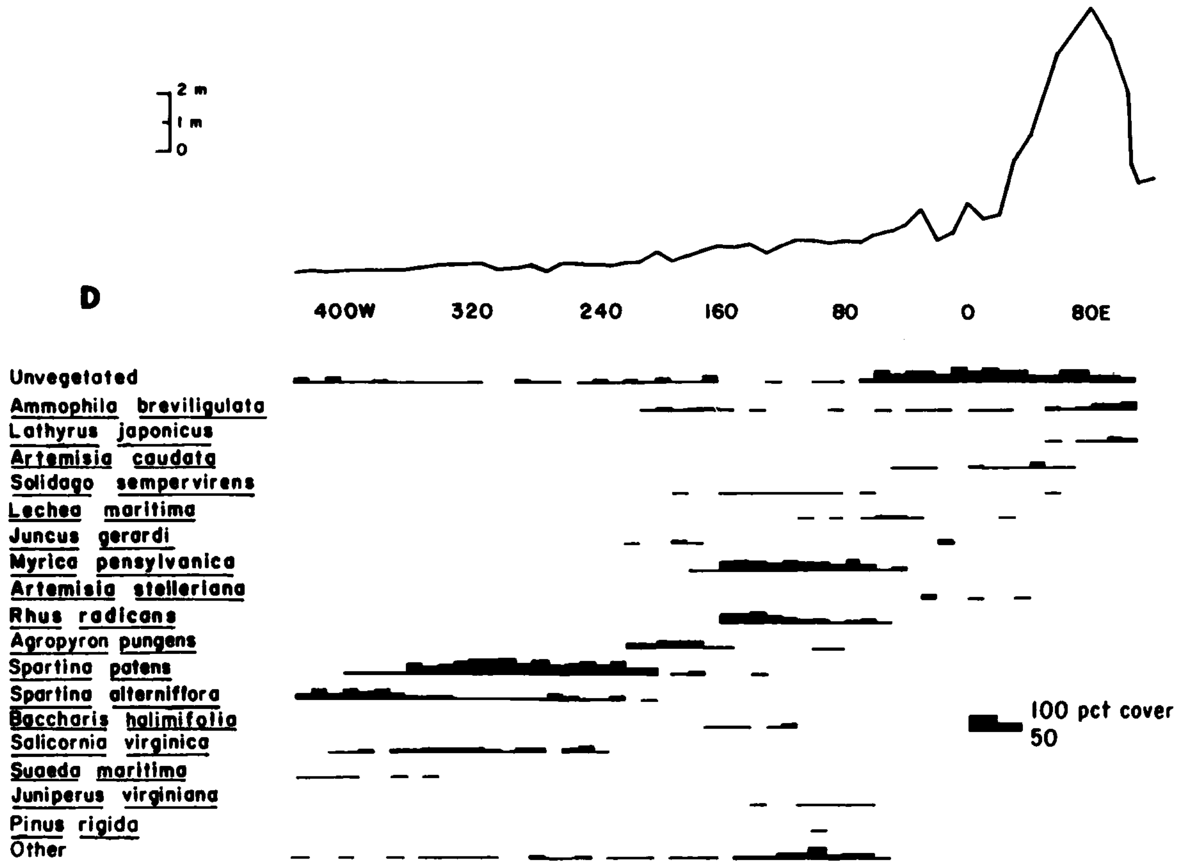

Figure 123. Vegetative-physiographic transect of belt D.

Two areas were chosen that have been significantly altered within the last 26 years. Because belt G was completely overwashed during 1952, all vegetative and physiographic features are very recent (Fig. 116). Belt K, located near the present spit terminus, consisted of discontinuous dunes arranged in spit recurves in 1952 (Fig. 124).

Belt G was located at the southern end of North Beach in 1868, immediately south of the 1846 inlet site (Fig. 90). In the 20 years after the area first formed, salt marsh had developed behind a very narrow dune line (Fig. 116). This marsh was not indicated on the 1886 map. Bay currents at the spit terminus may have eroded the young marsh. By 1938 a dune line broken by washover

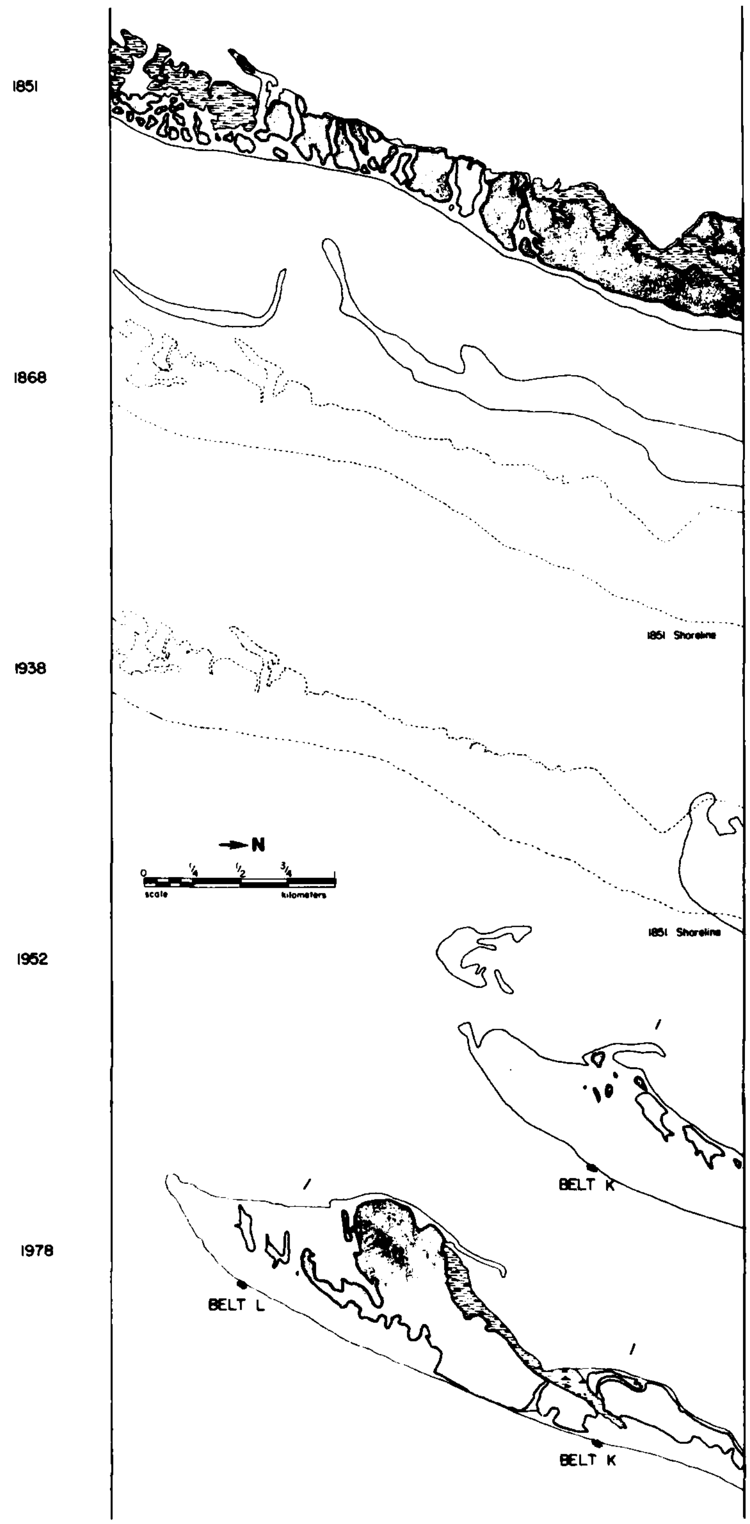

Figure 124. Historic maps of belts K and L.

breaches had developed with a narrow band of salt marsh along the bay shoreline. Bay shoreline erosion reduced the barrier width to 107 meters by 1941 (Table 54). In 1952 a massive overwash placed sediment in a large fan shape, extending as far as 405 meters beyond the bay shoreline, but 91 meters of the bayward perimeter of the washover was removed by tidal currents between 1952 and 1978.

The U.S. Army Corps of Engineers constructed sand dunes during 1965 and 1967 across the massive washover breach at belt G (U.S. Army Engineer Division, New England, 1979). By 1978 these dunes were 5 meters high, 100 meters wide, and continuous except for two breach washovers north and south of the belt (Fig. 125). Back-barrier dunes developed poorly since the artificial, seaward dunes reduced overwash and aeolian sand supply for dune building. A series of small, low dune ridges, which were remnants of drift-line dunes that failed to fuse into the dune line, were interspersed throughout the salt marsh. Since these low ridges acted as barriers to frequent tidal flooding from the bay side, much of the young salt marsh at belt G had a very low biomass.

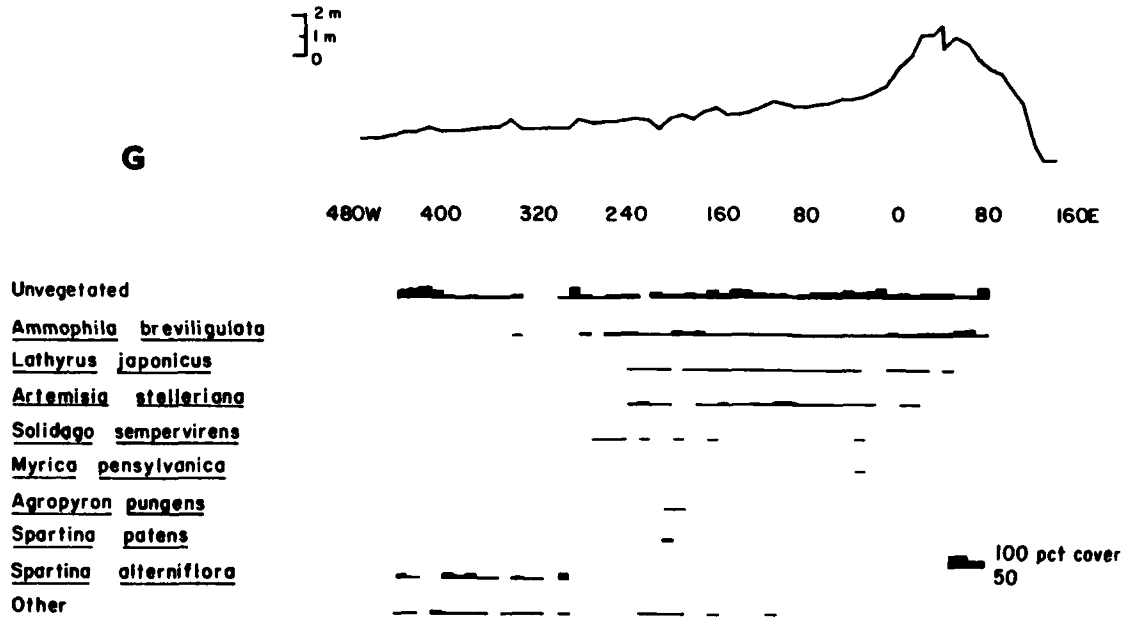

Figure 125. Vegetative-physiographic transect of belt G.

Belt K is less than 40 years old since New North Beach had not extended as far south as belt K in 1938 (Figs. 90 and 124). This belt was very broad in 1952, and was characterized by three spit recurves. Two of these recurves had fused by 1970, and a salt marsh developed in the protected center of the barrier. Sheet overwash buried sections of the seaward recurve in 1978.

The seaward spit recurve had been severely eroded by ocean waves and currents. Dense, healthy *Ammophila breviligulata* grew on both the ocean- and bay-facing dunes (Fig. 126). Toward the center of the western spit recurve, depauperate *Ammophila breviligulata* grew with extensive stands of *Artemisia caudata* and *Chrysopsis falcata*. Although the belt is only 26 years old, *Ammophila breviligulata* has already begun to decline in vigor in the interior of the dune field in the absence of accreting sand due to the development of high foredunes.

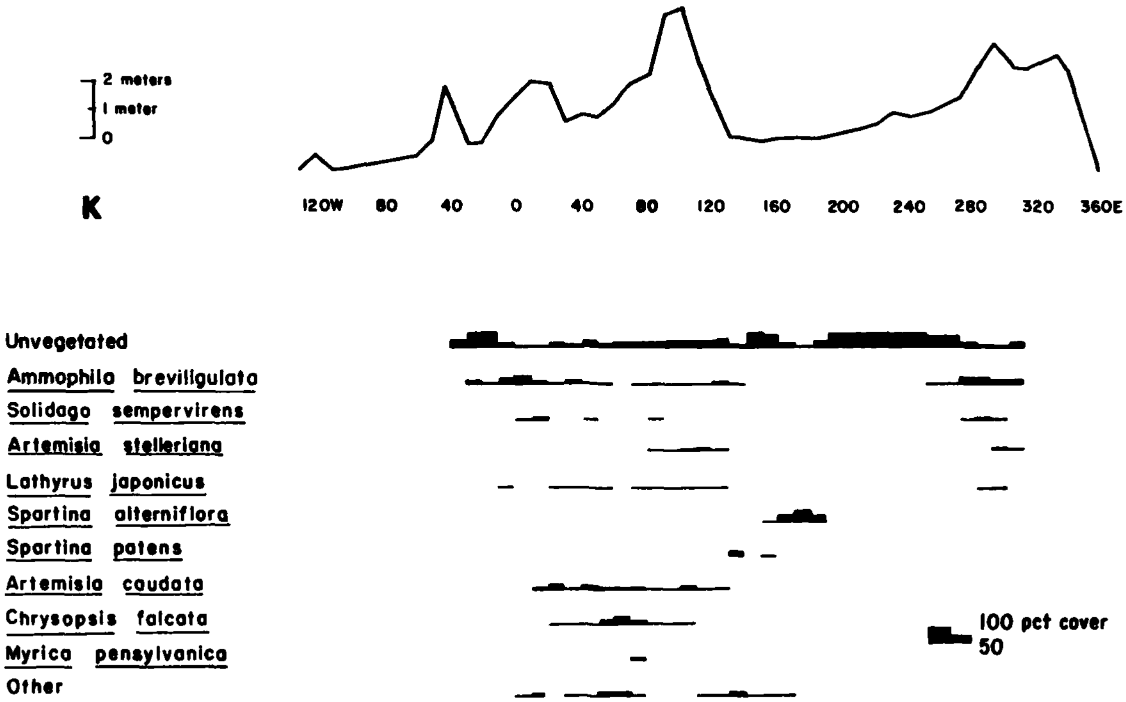

Figure 126. Vegetative-physiographic transect of belt K.

Four belts were chosen where vegetation and physiographic features had developed within the past 10 years. Belts X and Y were fenced and planted with *Ammophila breviligulata* by the U.S. Army Corps of Engineers in 1968 in a research project studying rates of dune development under a variety of conditions (Knutson, *1980; Fig. 118*). *Belt J was completely overwashed* in 1978 (Fig. 120), and belt L, located at the southern end of North Beach, has developed since 1970 (Fig. 124).

Belts X and Y are located on Nauset Spit-Orleans near Nauset Heights. In 1978 the dune line constructed by the U.S. Army Corps of Engineers was 120 meters wide and 4.4 meters high at belt X and 100 meters wide and 3.5 meters high at belt Y (Figs. 127 and 128). *Elymus arenarius* (sea-lyme grass) and *Carex kobomugi* were planted at belt X and have survived in limited areas among poorly developed stands of *Ammophila breviligulata*. Occasional drift-line species were the only other plants present in these belts. Salt marsh had not developed along the bay shore because the barrier was narrowed at this location by swift bay channel currents.

Belt J is located east of Chatham Light in the very narrow section of New North Beach, which has in 26 years migrated landward a distance exceeding its own width without inlet formation (Figs. 90 and 120). This belt, which was extremely wide (620 meters) when it first formed at the spit terminus, narrowed from both the ocean and bay sides (Table 54). Ocean shoreline erosion averaged 6.8 meters per year between 1952 and 1978.

Parts of belt J were planted by the Massachusetts Beach Buggy Association in 1976. The entire belt was overwashed in 1978 with some sediment added to the bay shore. Along 80 meters of the belt transect, *Ammophila breviligulata* was buried by washover deposits and recovered. Dune vegetation biomass at belt J was among the highest along the Nauset Spit system (Table 55). Only one other species, *Salsola kali*, was present in the entire belt (Fig. 129).

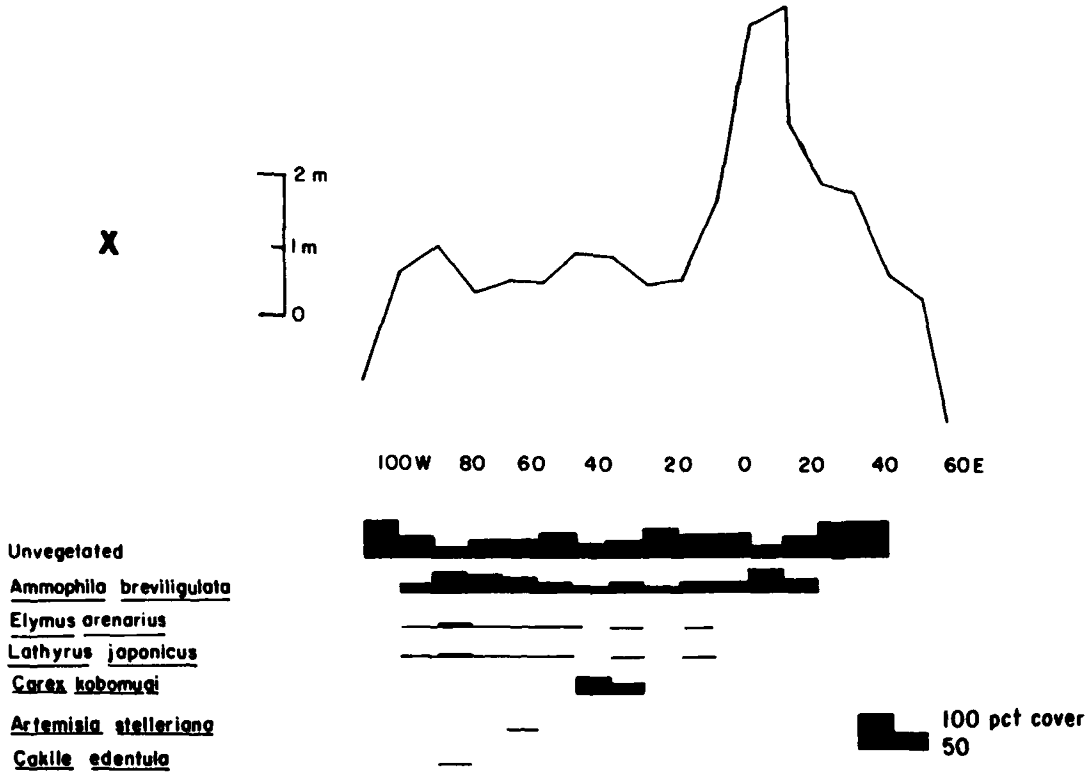

Figure 127. Vegetative-physiographic transect of belt X.

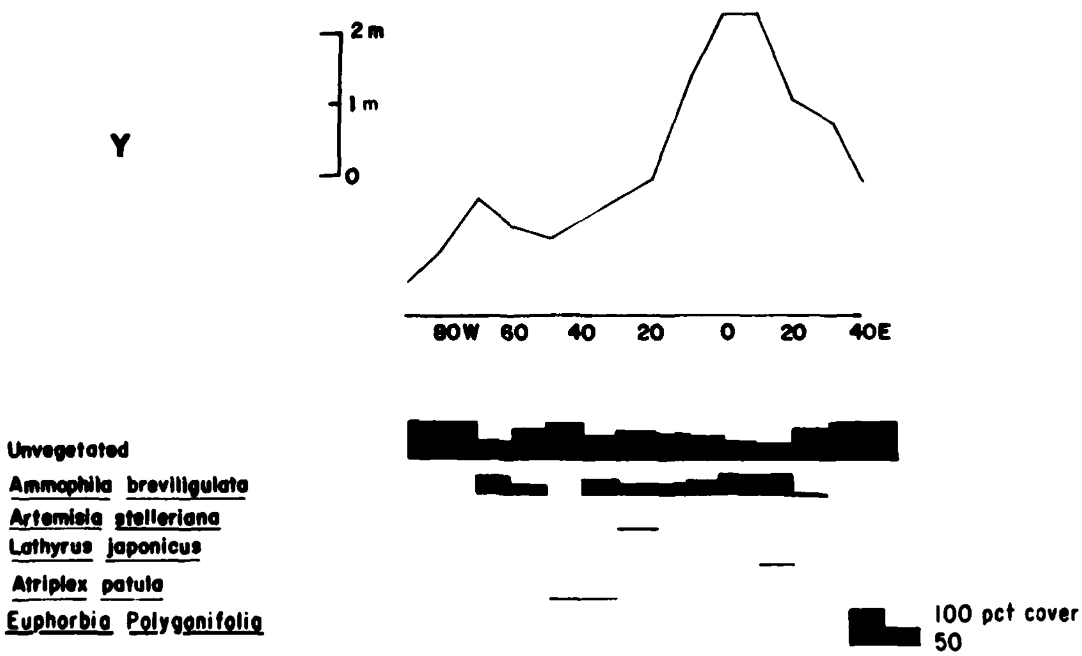

Figure 128. Vegetative-physiographic transect of belt Y.

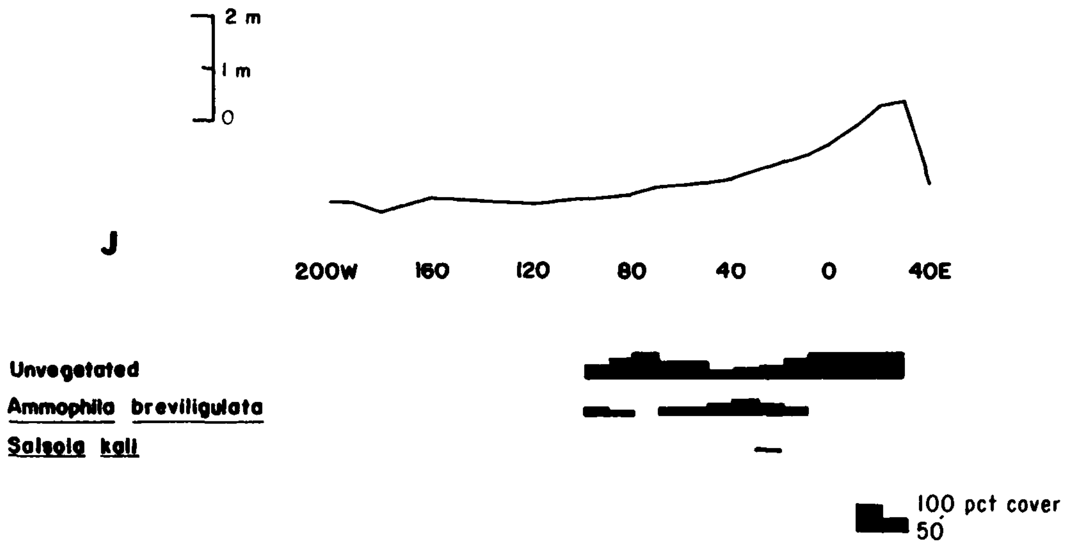

Figure 129. Vegetative-physiographic transect of belt J.

Belt L is located at the southern end of North Beach. Until 1970 this belt was characterized by unvegetated washovers (Fig. 124), but two well-developed spit recurves had developed by 1978. The seaward recurve had dunes 1.75 meters high and 110 meters wide; the back-barrier recurve was 3 meters high and 70 meters wide (Fig. 130). Natural dunes as formidable and as rapidly built as those constructed at belts X and Y were present at belt L in 1978. These dunes rapidly increased in elevation benefiting from the abundant sand available for dune building at the spit terminus. Winds traveling over barren sand sources from all directions added sediment to the dunes. The greatest dune development occurred on the western recurve reflecting the predominant northwest and southwest winds on Cape Cod. Since these dunes were accreting very rapidly, *Ammophila breviligulata* was the only major plant species sampled within the belt.

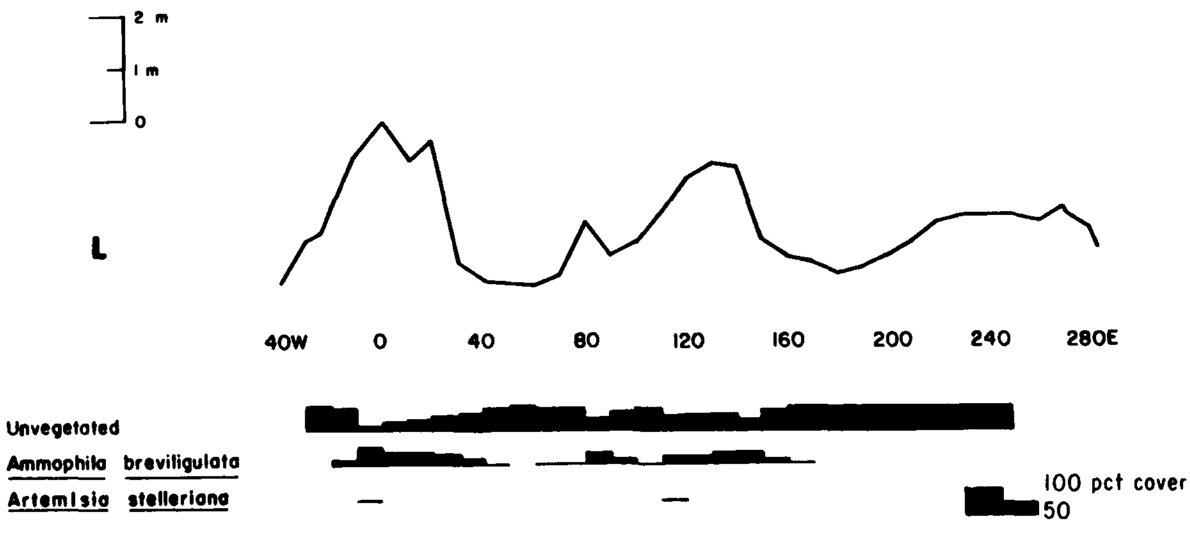

Figure 130. Vegetative-physiographic transect of belt L.

d. Analysis of Data. Species lists have been compiled for all belts sampled on Nauset Spit. Field data were transferred to tables in order to correlate belt maps with quantitative vegetation information. Percent cover, percent frequency, relative cover, and relative frequency were calculated for each belt. Cover classes were converted to an appropriate percentage of 25 to correlate cover class with point-intercept information.

Species diversity was calculated for each site, using Simpson's index (Table 56). This index indicated that species diversity increases very rapidly following an overwash. Belt J, which overwashed in February 1978, had an extremely low species diversity index (0.0052) since only *Ammophila breviligulata* was able to recover from burial in the area. Belts X (0.3540) and Y (0.0767), stabilized by the U.S. Army Corps of Engineers within the last 10 years, also had very low species diversity indexes reflecting the selection pressure of rapid vertical accretion. Belts older than 10 years did not differ markedly from one another in relation to age, even when drift-line species, more common in recently developed areas, were not considered. Species richness was low in very recent areas, but as with species diversity, it did not show pronounced trends in belts older than 10 years (Table 56).

Table 56. Species number and diversity index for each belt site on North Beach.

Belt	No. of species	No. of species sampled	Diversity index
Oldest			
A	36	29	0.7457
B	45	31	0.8285
C	44	31	0.8596
E	54	37	0.7358
F	41	32	0.7842
Z	15	11	0.6205
40 to 92 yrs old			
D	38	36	0.8606
H	26	15	0.4739
I	45	31	0.8375
Approx. 26 yrs old			
G	44	33	0.7463
K	31	19	0.7751
Less than 10 yrs old			
J	3	2	0.0052
L	20	6	0.1035
X	12	6	0.3540
Y	8	5	0.0767

A prominence value (relative cover × relative frequency$^{1/2}$) was calculated for each species within each belt. The prominence value (Disraeli and Fonda, 1979) weights favored larger plants, which presumably have greater community importance. A similarity matrix was constructed using a modification of the Gleason similarity index:

$$\frac{2(a)}{b + c} \times 100$$

where a is the lower of the two relative cover values for a species that is held in common between two sites, b is the sum of the relative covers of one site, and c is the sum of the relative covers of the second site. A similarity index is a quantitative means of determining the similarity between two sites. The range of index values is from 0 (no species in common) to 100 (all species in common with equal prominence). For this analysis, the prominence value was used rather than relative cover alone, to take into account more detailed data. Table 57 is a matrix of all possible comparisons.

Based on the similarity matrix, a two-dimensional ordination was constructed of the 15 sampled belts (Beals, 1960; Fig. 131). An ordination is a means of spatially separating samples based on any similar quantitative measurement. Those belts which appear farthest apart are the least similar; those that are closest are most similar. By assessing the community structure of each area separately and all areas as a whole, subtle distinctions can be made between different types of communities and the different structures of these communities with relation to the length of time since overwash.

From the two-dimensional ordination it is evident that, vegetatively, belts X and Y (the two CERC areas) are grouped with belts that have recently developed or overwashed, belts J and L (Fig. 131; group I). These belts are principally dominated by *Ammophila breviligulata* with consistent drift-line subdominants. These young areas have low species richness, particularly when drift-line species are discounted (Table 56). Overall biomass is high on young dunes, with the highest *Ammophila breviligulata* biomass found on accreting dunes (Table 55).

Oldest sites (belts B, C, E, and F) which have not overwashed in the last 90 years are grouped broadly to the far left (Fig. 131, group II). These areas have highly diversified, broad sand dunes and salt marshes. In all four of these belts the dunes are 5 to 10 meters high and continuous. Belts B and F are grouped close together because they both have well-developed *Hudsonia* communities with *Spartina patens* and *Agropyron pungens* characteristic of marginally supratidal substrate. These grasslands may indicate that these belts formed as a result of massive overwash which, when deflated, varied gradually in elevation from low and high marsh zones to a broad transition zone between marsh and dune. Supratidal grassland communities are absent from young areas.

Belt A groups with the older belts (group II) even though the shrub and dune communities have only developed since 1952. The salt marsh and grassland at belt A are very similar to belts B, C, E, and F. A broad *Spartina patens* high marsh is bordered by a narrow, poorly productive *Spartina alterniflora* low marsh. The dune and shrub communities of belt A also do not differ greatly from the other belts, indicating that in as little as 26 years dunes can form and become senescent. The *Ammophila breviligulata* biomass on the west side of the dune field is as depauperate as any on North Beach. The shrub community at belt A is as diversified as the communities at belts B or C.

Table 57. Similarity matrix of the 15 belt transects on North Beach.

Belts	A	B	C	D	E	F	G	H	I	J	K	L	X	Y	Z
A	----	71.4	45.2	50.2	67.6	52.8	30.0	32.7	41.0	14.0	32.6	14.3	19.0	15.0	30.2
B	28.6	----	81.4	55.3	57.6	58.7	37.1	37.0	54.7	15.9	41.5	16.4	20.9	17.2	32.5
C	54.8	18.6	----	32.6	16.4	37.3	36.0	32.0	61.5	17.4	39.7	18.1	23.9	19.5	38.3
D	44.8	44.7	67.4	----	59.7	54.1	24.6	17.7	34.8	3.4	22.4	3.5	4.6	3.8	14.4
E	32.4	42.4	83.6	40.3	----	42.4	19.4	18.2	22.9	2.7	18.7	2.8	3.9	3.1	8.1
F	47.2	41.3	62.1	45.9	57.6	----	41.6	30.4	37.5	11.8	37.8	12.2	18.2	12.8	27.9
G	70.0	62.9	64.0	75.4	80.6	58.4	----	46.9	47.4	33.0	69.3	34.0	46.9	36.2	60.8
H	67.3	68.0	68.0	82.3	81.8	69.6	53.1	----	44.5	68.2	45.0	69.6	84.6	72.1	55.0
I	59.0	45.3	38.5	65.2	77.1	62.5	52.6	55.5	----	24.5	52.8	25.0	33.1	26.3	44.0
J	86.0	84.1	82.6	96.6	97.3	88.2	67.0	31.8	75.5	----	30.6	98.1	74.0	94.8	38.9
K	67.4	58.5	60.3	77.6	81.3	62.2	40.7	55.0	47.2	69.4	----	31.6	41.2	33.6	57.9
L	85.7	83.6	81.4	96.5	97.2	87.8	66.0	30.4	75.0	1.9	68.4	----	75.5	96.6	39.8
X	81.0	79.1	76.1	95.4	96.1	81.8	53.1	15.4	66.9	26.0	58.8	24.5	----	78.1	52.9
Y	85.0	82.8	80.5	96.2	96.9	87.2	63.8	21.9	73.7	5.2	66.4	3.4	21.9	----	44.5
Z	69.8	67.5	61.7	85.6	91.9	72.1	39.2	45.0	51.0	61.1	42.1	60.2	47.1	55.5	----

Dissimilarity index

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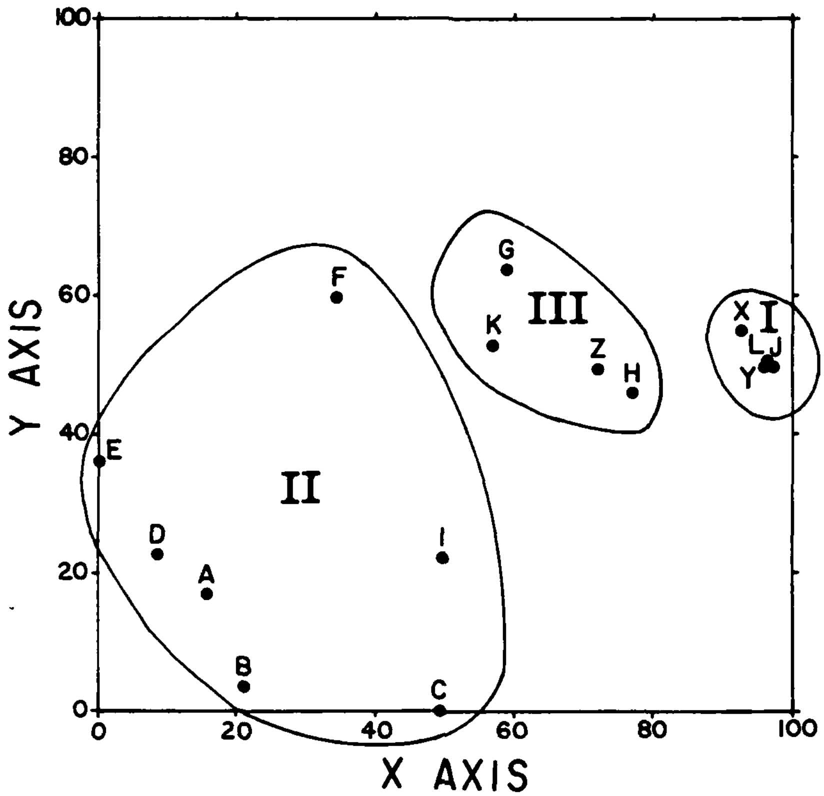

Figure 131. Ordination of 15 belts on North Beach.

Belt D also groups with the older belts on North Beach (group II). This area, which was barren sand in 1938, has developed all the major barrier communities in only 40 years. Of particular interest is the highly diversified salt marsh at belt D. *Spartina alterniflora* biomass is low with many associates. The dunes at belt D are 6 meters high and broad as a result of reworking of the 1938 washover.

Belt I also generally groups with the older belts (group II). Although this belt has formed within the last 50 years, it has well-developed shrub and grassland communities. *Ammophila breviligulata* in the dune community has the highest productivity sampled on North Beach. This dune community completely overwashed in 1978.

Group III (belts G, H, K, and Z) fall in an intermediate position between the young belts (group I) and the older belts (group II). Belts G and K have developed since 1952, and belt H, although initially formed in the 1930's, was partially overwashed in 1978. All three belts have a mixture of poorly and well-developed dunes. Salt marshes are restricted to localized areas. Belt G differs from all other areas because it has a very broad zone with depauperate dune vegetation. This massive washover in 1952 received substantial inputs of sand from overwash until the 1960's when the dune field became continuous. The embryonic dunes, formed on the back barrier, rapidly deflated, resulting in the senescence of *Ammophila breviligulata*. This belt, which was formed similarly to belt D, does not appear to be developing in the same manner. It is possible that at belt D, overwash continued for many years allowing substantial back dunes to form, and that rapid dune development at belt G,

resulting from U.S. Army Corps of Engineers projects, reduced washover sediment available for dune building. The depauperate section of belt G may, in time, be colonized by shrubs as has occurred at belt D. It should be noted, however, that belt D is backed by glacial headlands which provide an adjacent seed source for woody species, whereas belt G is flanked by open water (Pleasant Bay).

From these vegetative physiographic transects, it is apparent that the rate of development of all plant communities and physiographic features on North Beach is extremely rapid. Dunes have been evident from aerial photography analysis on washovers deposited over salt marshes in as little as 3 years. Since the major dune species on North Beach can recover from substantial overwash burial, washovers on dune communities may appear unvegetated on aerial photos when, in fact, dune building is occurring very rapidly in the area. The greatest *Ammophila breviligulata* biomass on North Beach occurs in areas that have recently overwashed (belts H, I, and J; Table 55). These biomass data even exceed data collected on building foredunes (belts K, L, X, and Y). As much as 70 centimeters of sand can be added to a low dune by overwash in a single year (see Sec. II).

Most new dune development has been associated with massive washovers on Old North Beach and with spit elongation on New North Beach and Nauset Spit-Orleans. Dune development on massive washovers at North Beach often begins at the western edge of the feature in drift lines. Often these dunes at the bayward edge do not survive once overwash and continued sand supplies are reduced or eliminated. These low dunes may deflate rapidly and become colonized by high marsh vegetation, or if these dunes do not deflate to high marsh elevations, *Agropyron pungens* may colonize these slightly elevated sites.

Dunes will, in a short while, build on the landward part of massive washovers at the location of remnant dunes or drift piles. Small washover fans and breaches may provide some sand for the expansion of the dune line locally, but do not play a major role in dune-building processes and landward displacement of the physiographic zones of a barrier system.

Species diversity on sand dunes at North Beach increases after the initial rapid building period, but does not continue to increase with time (Table 56). Once a dune no longer increases in elevation, several plant species rapidly invade less vigorous stands of *Ammophila breviligulata*. Shrubs may colonize the area if foredune height reduces salt spray and seeds are available. If the site remains stable for many years, stands of *Ammophila breviligulata* may begin to decline in vigor, giving way to *Hudsonia tomentosa*, *Chrysopsis falcata*, *Artemisia caudata*, *Lechea maritima* (pinweed), and *Cladonia* spp. These species can be used as indicators of substrate stability, but may reflect only very recent conditions; senescent dune zones develop rapidly. Belt K, which is less than 26 years old, has a broad, stable dune area in the interior of two large spit recurves with extensive stands of dead and dying *Ammophila breviligulata*.

Spit recurves have developed at the terminus of North Beach opposite embayments in the Chatham mainland, increasing dune field and barrier width. In several areas (belts H, I, and J), these recurves have been truncated on the bay side by tidal currents in Chatham Harbor, resulting in apparent parallel dune ridges on the bay and ocean shorelines of the barrier. The bay shoreline dunes should not be confused with washover-derived dunes which, if isolated from the ocean dune line, are also low in elevation.

Salt marshes develop rapidly on North Beach, although marsh development is not as predictable as dune development. In as little as 10 years, salt marshes have become visible on aerial photos in areas that had been washovers. Only with shallow deposits at the outer edges of washovers do salt-marsh species recover from burial. These recovering species often do not survive unless overwash activity is reduced in the area. Although rhizome outgrowth into shallow bay water has increased marsh area along some sections of Old North Beach, most new salt marshes develop on washovers. In some sections of Old North Beach, cores and trenches reveal layers of salt-marsh peat overlain by washover deposits, which have been recolonized by marsh vegetation. Marshes on North Beach tend to survive in place for longer periods of time than dunes, because of their bayward position and protection afforded by the dune line.

Shrub communities have also developed rapidly on North Beach. At belts A, D, and I, shrub communities have developed in less than 40 years. Three pitch pines at belt I are 5 meters tall and 10 centimeters in diameter, but these trees may have been planted by homeowners. At belt D a felled juniper that had not been buried by overwash was aged at 32 years, although the belt was overwashed 40 years ago. The development of shrub communities is dependent on protection from salt spray and seed availability. Belts closer to the glacial headlands in Orleans undoubtedly have greater access to seed supplies of *Myrica*, *Juniperus*, *Salix*, *Rhus*, and *Rubus*, which are common at belts A and D. Shrub communities are not a good indicator of the age of a site over 25 years, unless dating of individual trees or shrubs is undertaken.

Supratidal grassland communities are present in many areas on Old North Beach and appear to be associated with older washovers. All the species in this zone are at least marginally salt tolerant. The grassland community on North Beach may be equivalent to the narrow ecotone in Nauset Spit-Eastham between dune and salt-marsh communities and may only exist as a broad area on North Beach because the tidal range is very low in upper Pleasant Bay.

In general, classical ecological succession does not appear to occur on North Beach. The entire spit system is migrating rapidly landward by overwash processes and inlet dynamics. Few areas on the spit are older than 110 years. With the exception of members of the stable dune communities, all the species dominant on North Beach can grow in bare sandy substrate. The particular species colonizing an area is dependent on environmental factors operating on undeveloped soil, such as the level of tidal flooding, soil salinity, soil moisture, exposure to salt spray, degree of substrate stability, and propagule availability.

V. DISCUSSION

1. Migrational Processes.

Many barrier beaches along the east coast of the United States are undergoing landward retreat in response to sea level rise. Landward displacement can be divided into two separate phenomena: migration of the barrier landform as a whole and migration of physiographic features (e.g., sand dunes) on the barrier surface. The barrier width can be defined as the continuous unit extending from the berm to the bay shoreline or first major waterway. In order for landward barrier migration to occur, material must be eroded along

the oceanfront, and material must be added to the back-barrier margin. If sand is only lost along the oceanfront, the barrier has simply eroded. If sand is only added to the backshore without shoreline erosion, the barrier has widened. Barrier migration occurs over long periods of time and is often the result of continuous shoreline erosion with periodic back-barrier extension resulting from inlet activity or overwash.

Surficial features, such as dunes, may move over the subaerial barrier without the extension of the barrier beach as a whole toward the mainland. Overwash and aeolian processes may transport sand across the dune line. On northeast barriers, this sand is often deposited on salt-marsh vegetation, which does not recover from deep burial (greater than 33 centimeters). Dune plants often colonize these deposits, resulting in landward displacement of the dune line at the expense of salt-marsh vegetation. If new dunes form on the site of previous salt marshes and no new substrate is added to the bay shoreline, the barrier as a whole has not migrated.

There are three general mechanisms by which barrier beaches move landward: (a) aeolian, (b) overwash, and (c) inlet processes. Along some sections of the east and gulf coasts, one of these processes may dominate. For instance, large quantities of sand have been transported beyond the back-barrier margin by prevailing onshore winds at Padre Island, Texas (Mathewson, Clary, and Stinson, 1975). Overwash processes have been shown to dominate some small microtidal barriers (Maurmeyer, 1978). Sediment is carried across the barrier in either small pulses with washovers, adding little sediment to the back barrier or, on a larger scale, as long barrier sections are overwashed, contributing great volumes of sand to the bay shoreline. By far the most prevalent means of barrier migration along the east coast is by inlet-associated sand transport.

At Nauset Spit, inlets historically have played a major role in landward sediment transfers along all sectors and presently in many areas. Nauset Bay is essentially filled with marsh islands constructed on flood-tidal delta deposits. Nauset Inlet continues periodically to migrate north and south, introducing additional material to fill depressions while still maintaining an inlet channel. The upper reaches of Pleasant Bay have also experienced much sedimentation and, hence, shallowing by inlet activity. The earliest records date to 1602 when explorers noted a series of inlets cut through the North Beach barrier. This spit segment has undergone at least three different series of inlet formation with subsequent inlet migration downdrift. In this process of cyclic inlet breaching and spit regeneration, the entire barrier structure has been effectively displaced landward. Only at Chatham Harbor has the barrier rebuilt in the same general location during the last cycle (1860's to present) since a particular hydraulic area of the channel must be maintained to accommodate the tidal flow within Pleasant Bay. North Beach may now be in a position that the historic barrier spit fronting the glacial headlands of Chatham will not reform, resulting in future cliff erosion by direct ocean wave attack.

During this study of barrier beach processes along Nauset Spit, the importance of inlet dynamics and overwash in barrier migration became evident. Barrier migration was studied using shallow cores, early maps, aerial photography, and individual storm data. Core data showed that overwash previously occurred along some sections of Nauset. On Nauset Spit-Eastham, a salt marsh existed behind barrier dunes approximately 815 years B.P. This marsh was

subsequently buried with overwash sand which was carried up to 250 meters beyond the bayward edge of the marsh. Sediment deposited along the bay shoreline was colonized by salt-marsh vegetation, and sand subsequently placed on top of the salt marsh was colonized by dune vegetation.

Nauset Spit-Eastham was extensively overwashed during the February 1978 northeaster. While 75 percent of the dune line was leveled and 32 percent of the salt marsh was buried, only 1.7 hectares of new substrate was added along the bay margin, resulting in barrier migration. Large-scale migration of Nauset Spit-Eastham did not occur during this major storm because the barrier was already widened prior to the storm due to the major overwash event during the 1700's. Reworking of these extensive washover deposits will eventually lead to the formation of a new dune line in a position landward of prestorm dunes. Overwash will have resulted in the migration of surface features along Nauset Spit-Eastham. Because the basal peat layer will prevent future inlet activity along the northeast section of Nauset Spit-Eastham, overwash will eventually result in landward migration of this section of the spit system.

On Old North Beach, core data revealed that washover sand had buried a salt marsh approximately 200 years ago; peaty material was outcropping along the ocean beach in 1978. Salt-marsh vegetation had colonized this washover surface and survived long enough to form a peat layer before being buried by overwash again. Thus, barrier rollover at this North Beach location and at the location of the sinking of the *Sparrow-Hawk* in 1626 has been determined to be less than 250 years.

Overwash has been a major factor in the evolution of Old North Beach; inlets have not affected this section of Nauset during the past 110 years. While an average of 242 meters was lost to shoreline erosion during this period, average barrier width decreased by only 90 meters since overwash widened the barrier in many locations. Barrier width along 37 percent of Old North Beach decreased because glacial deposits abutting the barrier have made further migration impossible. Eventually the glacial highlands of Little Pocket Island and Nauset Heights will be exposed to wave attack and the barrier beach will be converted by erosion into a beach fronting a headland at these locations.

2. Vegetative Response to Overwash.

The response of barrier-beach vegetation to overwash burial was studied using U.S. Coast Survey maps and aerial photos as well as prestorm and poststorm vegetation and elevation data. The location of dunes, salt marshes, shrubs, and washovers was mapped along the spit system for periods from 1851 to 1978 to determine the rate of plant community development and morphological changes along the barrier system. Vegetation and elevation data were collected in 1977 and compared to data acquired after the February 1978 northeaster. The immediate response of major dune and salt-marsh species to overwash and the colonization of washovers were documented from these data.

Dunes play an important role in the stabilization of barrier beaches. Dunes, which act as barriers to wave attack during all but the most severe storms, provide protection for back-barrier vegetation. Salt-marsh plants become established in low-energy, intertidal regions of the barrier. Areas that are subject to frequent overwash or swift bay-side currents do not

support salt-marsh vegetation. Dunes also reduce salt-spray intensity, which allows the establishment of salt-intolerant species to the lee of this barrier. Finally, dunes act as sediment reservoirs for both nourishment of beaches during storms and for washover deposits. During storms some of the sediment removed from the beach by wave activity is replaced by dune-face erosion. Surges that cross the berm crest carry beach and eroded dune sediment to landward positions. This sediment is reworked by the wind during interstorm periods. On Nauset Spit, prevailing winds transport much of the washover sediment eastward. Remnant and newly established dunes trap some of this sand, eventually recreating a continuous dune line.

In 1978 the dune line at Nauset Spit-Eastham was high and almost continuous. Most of the dunes along Nauset Spit-Eastham affected by the February 1978 overwash were leveled and the vegetative surface was eroded. Some sections of the dune at site 3 were, however, buried by up to 67 centimeters of overwash sand without disturbing the vegetative surface. The four major dune species found on the Nauset Spit system, *Ammophila breviligulata*, *Artemisia stelleriana*, *Lathyrus japonicus*, and *Solidago sempervirens*, were present in quadrats sampled before and after overwash at this location. All four species were able to recover from deep overwash burial. Washover deposition equaled typical high, annual levels of wind-transported sand deposition in dunes. On low-lying, well-vegetated dunes, overwash plays an important role in dune building.

Following overwash, wind deflation of extensive washover flats aids in the redevelopment of the dune line. At Nauset Spit the prevailing sand-transporting winds move sand offshore; remnant dunes trap much of the material deflated from washovers. Along the outer edges of the washover, drift material is deposited by spring high tides. Sand reworked from the washover also accumulates differentially in the vicinity of emerging drift-line plants, thus building new dunes on the fan surface through time.

Shrub communities are found in areas of North Beach protected from salt spray. The frequency of shrubs decreases with distance from the glacial headlands at Nauset Heights, reflecting a decrease in stability of the barrier and a decrease in propagule availability. Shrubs have little importance in the maintenance of the physical stability of the barrier since a cohesive substrate has not been developed that could appreciably slow erosion and downward cutting during major storms.

Many of the shrubs on northeast barrier beaches appear to recover from overwash burial. *Rosa rugosa*, *Myrica pensylvanica*, and *Prunus maritima*, major shrub species on Nauset, survived burial of lower plant parts. Changes in water-table height caused by increased elevation may lead to anaerobic conditions in the shrub root zones; therefore, overwash deposition may eventually kill these plants. Major shrub communities on Nauset do not appear to grow through washover sediment and reestablish a shrub community. Isolated plants have recovered, however, and have survived burial for many years.

An aerial photography analysis indicated that shrub communities became established on new washover substrate in as little as 26 years. On Nauset, shrub species generally invade bare, stable washover sediment that is protected from high levels of salt spray. *Ammophila breviligulata* may have grown briefly in the area, but undoubtedly does not alter the sandy surface appreciably.

Salt marshes are important in contributing organic material to the bay and in providing stability to the barrier by the formation of peat. Over many years, salt marshes accumulate fine-grained sediment and organic material, building cohesive peat. Peat prevents excessive scouring during overwash, which could lead to inlet formation. Peat outcrops along the ocean beach also slow shoreline erosion and, as at the southern end of Nauset Spit-Eastham, salt-marsh peat has apparently slowed the lateral, northward migration of Nauset Inlet.

Salt-marsh vegetation is generally not eroded by overwash surges. After crossing the dune zone, surges slow due to flow divergence and essentially stop where ponded bay waters are encountered.

Salt-marsh plants on Nauset Spit-Eastham were buried by as much as 110 centimeters of sand. Only *Spartina patens* and *Spartina alterniflora* were able to recover, in restricted areas, from more than 10 centimeters of overwash deposition; *Spartina patens* recovered from up to 33 centimeters of burial. Plants at prestorm high elevations recovered better than plants at lower elevations. Data obtained from shallow wells indicated that the ground water table is raised beneath washover deposits. Anaerobic conditions resulting from waterlogging may limit the recovery of *Spartina patens* at low elevations and in areas of deep burial.

Spartina alterniflora recovered from as much as 22 centimeters of washover sand in 1978. Unlike *Spartina patens*, burial recovery was best at lowest elevations. Higher elevations are less frequently flooded and soil salinity may increase beyond the tolerance levels of *Spartina alterniflora*.

Many of the *Spartina patens* and *Spartina alterniflora* plants that had recovered from burial in 1978 were either dead or dying by 1980. The larvae of a weevil had invaded the cortex of many *Spartina alterniflora* plants that were yellow and dying; many *Spartina patens* plants that had recovered in 1978 were dead in 1980 and had rotted at a point 5 to 10 centimeters before the surface. Sediment deposition may have raised the elevation-water table height to a point that plant vigor was lost and waterlogging produced anaerobic conditions, weakening and ultimately killing the plants.

The aerial photography analysis indicated that salt marshes can form in as little as 10 years on newly placed washovers, but new salt marshes do not form on barren, intertidal washovers until overwash pressures are reduced. Salt marshes are established either by rhizome outgrowth from recovering or adjacent marsh plants, by plant fragments eroded from creek margins, or by seed. Following overwash, both *Spartinas* are able to expand rapidly by rhizome extension. Plants at the margins of washovers will colonize intertidal washovers at a rate of approximately 1 meter per year. Blocks of salt-marsh peat (mainly *Spartina alterniflora*) with living plants are frequently eroded along creek margins and carried by tides to intertidal positions where roots develop, anchoring the peat block. Many of these blocks are ice-rafted to the upper range of *Spartina alterniflora*. Fragments of both *Spartina alterniflora* and *Spartina patens* are also occasionally found among drift material deposited following overwash at the outer margin of washovers by spring tides. *Spartina alterniflora* seedlings in drift lines did not survive the dry summers during the course of this study. *Spartina patens* var. *monogyna* survived in drift lines and expanded energetically during the following years. Seeds of both *Spartina alterniflora* and *Spartina patens*

germinate at the upper edge of the intertidal zone. During the 3 years of this study, *Spartina* seedlings were not found on recent washovers but were present in other upper-intertidal areas protected from overwash.

3. Barrier Migration Model.

Overwash and the vegetative response to overwash have played important roles in the landward migration of Nauset Spit. Washovers along Nauset can be divided into two types based on their size and influence in barrier migration: washover fans and flats. Washover fans form as breaches through the dune line and result in small amounts of sand deposition to the lee of the dune field (Fig. 132). Along the Nauset Spit system, these deposits are frequently placed on salt-marsh vegetation; recovery from burial occurs only at the edges of the washover where deposits are less than 34 centimeters for *Spartina patens* and 23 centimeters for *Spartina alterniflora*. Most marsh plants do not recover from burial, leaving the washover fan barren and subject to wind deflation. At Nauset Spit, the prevailing west winds carry washover sand to the beach and to the back dunes adjacent to the washover throat (Fig. 132,c).

The percentage of sand returned to the beach and lost from the system depends on the general form of the washover, prevailing wind directions, and the width of the washover throat. At the washover studied in detail along Nauset Spit-Eastham, 52 percent of the sediment deflated from the fan was added to the landward margin of the barrier dunes and 22 percent was returned to the ocean beach. Although 62 percent of the original deposit was redistributed by winds and tides, the entire washover remained above the general elevation range of salt-marsh species. The eventual plant communities that form on small washover fans are dependent on the elevation of the deflated surface as it is stabilized by vegetation.

Because the Nauset barrier system is oriented north to south and prevailing sand-transporting winds are from the west, there is little opportunity for dune-building on small washover fans since there is only a limited amount of sand in upwind positions. Low dunes may form on a washover fan, but washover sediment is reduced as dunes coalesce across the washover throat, and new dunes on washovers rapidly reach a maximum height and begin to deflate. After several years (5 to 7), a small washover fan appears as a crescent-shaped rise on the salt marsh adjacent to the dune line. The dune line may have migrated slightly landward as sand deflated from the washover and accumulated in back-barrier dunes (Fig. 132,d). The washover itself may be colonized by supratidal vegetation, which has built very low dunes. Otherwise, these dunes may have deflated and *Ammophila breviligulata*-dominated vegetation may be outcompeted by species adapted to periodic saltwater flooding, such as *Spartina patens* var. *monogyna* and *Agropyron pungens*. The net result of small-scale overwash is that the dune line is displaced slightly landward.

In the second case, large-scale washovers play a very important role in barrier migration (Fig. 133). Prior to overwash, the barrier beach may consist of a continuous dune line backed by salt marsh. During a major storm the barrier dune is eroded to a point where low elevation dunes and blowouts are overtopped by overwash surges. These surges erode an increasingly wide channel through the dune line by lateral cutting until broad sections of the dunes are entirely flattened (Fig. 133,c). During overwash, large volumes of sand may be carried from the beach and dune to the back barrier. Some of this sediment may be transported into the bay, resulting in landward extension of the barrier unit.

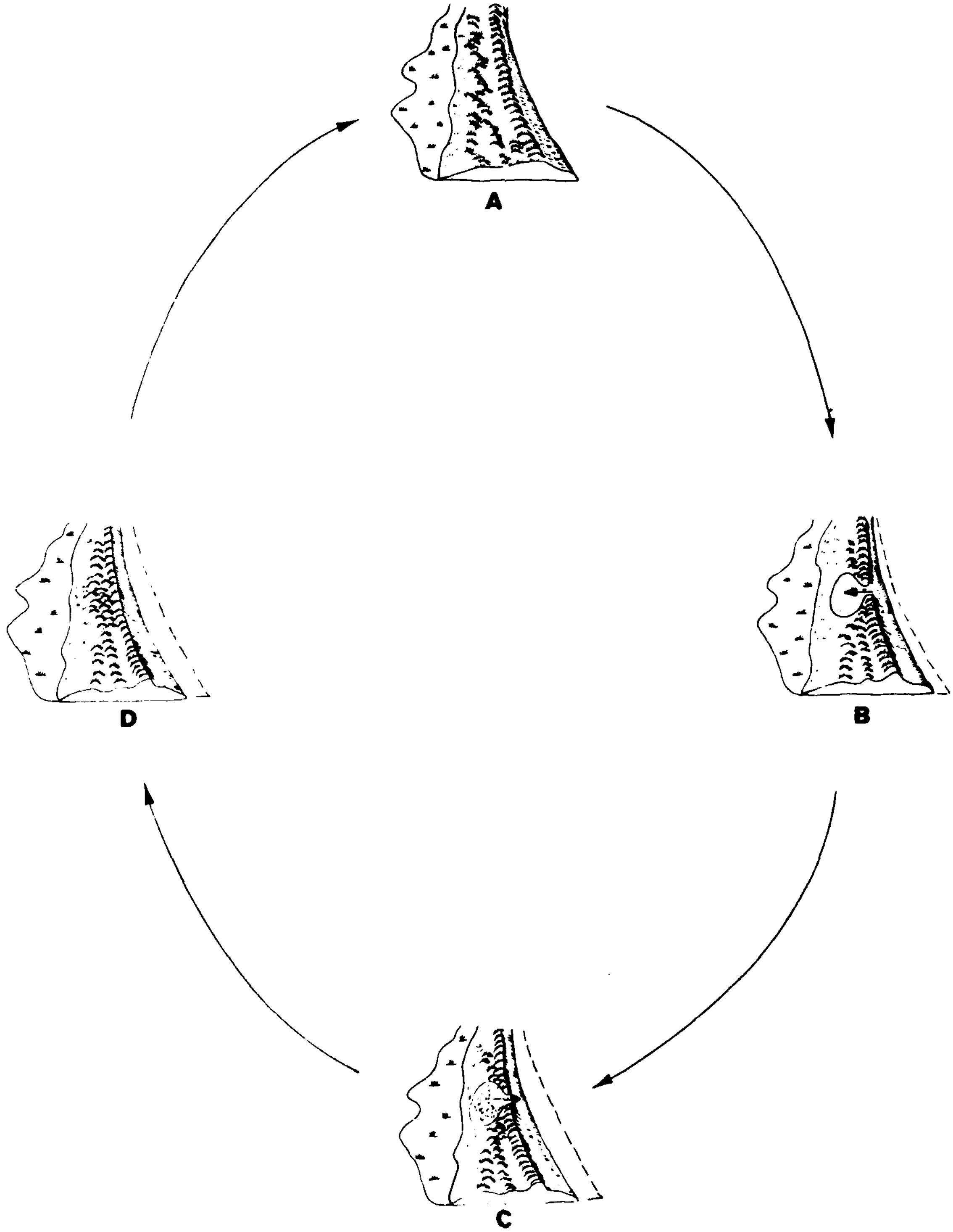

Figure 132. Model of role of overwash and vegetative response for small washover features.

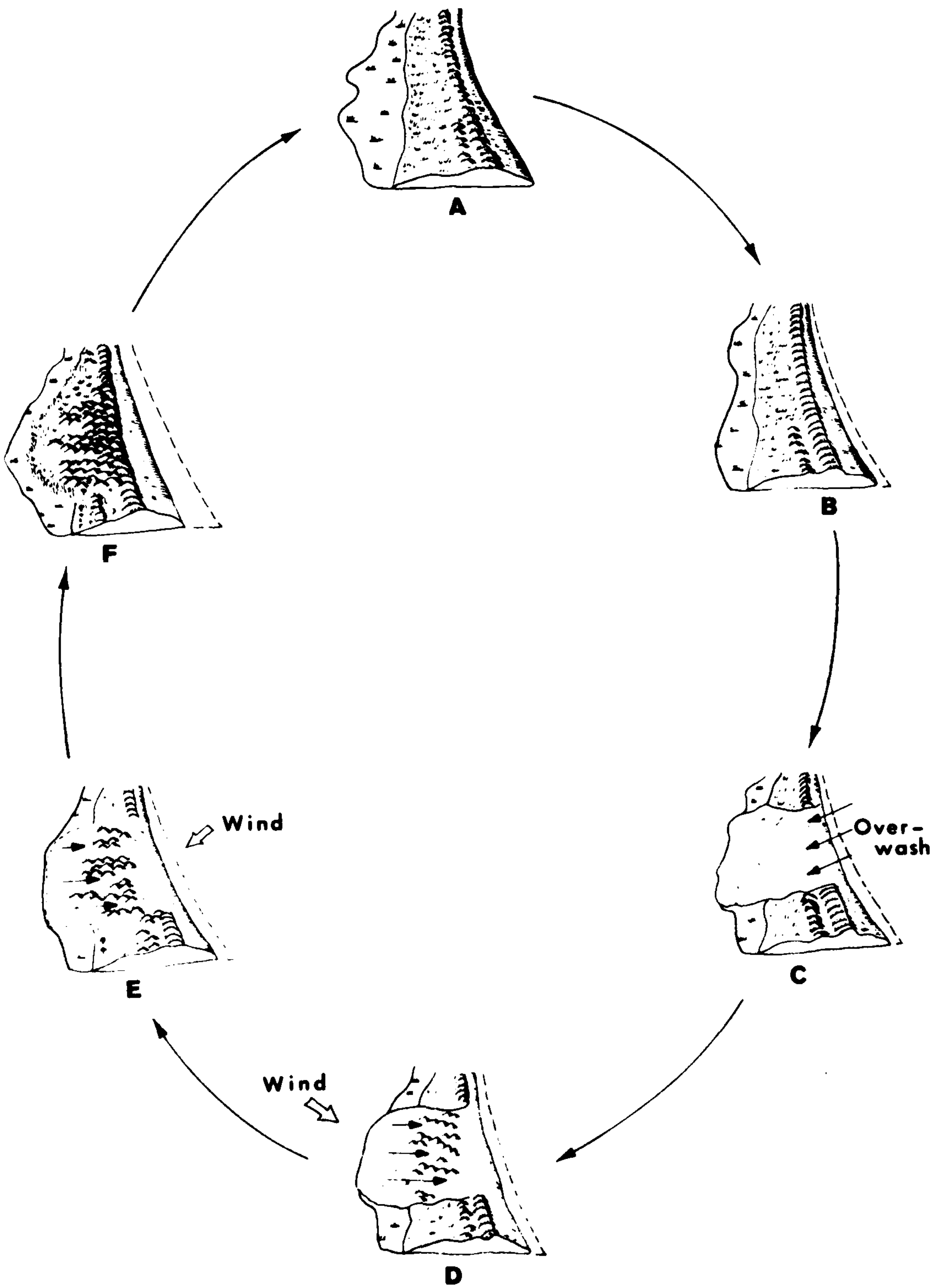

Figure 133. Model of role of overwash and vegetative response to overwash in the landward migration of a northeastern barrier beach.

Following overwash, organic debris is left on the washover surface in large clumps. Organized drift lines are also deposited along the outer margins of washover flats by spring high tides. The surface of the salt marsh is generally increased to elevations above the natural range of salt-marsh species. Fragments of dune plants present in drift lines regenerate and seeds germinate leading to the establishment of dune vegetation. As with the smaller washovers along Nauset Spit, the westerly winds deflate these washovers (Fig. 133,d). Most of the deflated sediment is returned to the ocean beach because extensive sections of the dune line have been leveled. Rhizome extension from surrounding dunes plays a smaller role in the stabilization and revegetation of large washovers than it does on smaller fans due to the large ratio of fan area to vegetative perimeter.

Dunes begin to develop in the location of drift material. In contrast to the case of small washovers, these dunes continue to build as overwash continues to add sediment to the back of the washover in upwind positions relative to the drift lines. The lack of constraining foredunes allows overwash to take place for several years (5 to 10), augmenting this sand supply. Drift-line dunes are usually not eroded during overwash since they are located in landward positions. During the final stages of dune recovery, washover passages through the foredunes periodically coalesce during windy, interstorm periods.

Eventually the dune line becomes continuous and the back barrier deflates to intertidal elevations at which moist sand will not saltate (Fig. 133). The net result of large-scale overwash is that after many years (10 to 20), all barrier features are displaced landward. New dunes, resulting from sand accumulation around vegetation initiated in drift lines, coalesce with vegetation expanding by rhizome extension from remnant dunes. New salt marsh forms in the lee of these dunes, and the barrier beach as a whole is displaced landward with the establishment of the same general physiographic features and vegetative composition.

4. Engineering Implications.

All sections of the Nauset Spit system are subject to dramatic changes either by inlet activity or overwash. The four units designated during this study are eroding at progressively faster rates with distance from the major source of sediment along Outer Cape Cod, the glacial cliffs. Increased erosion rates lead to more rapid landward migration and more unstable conditions. The outer shoreline appears to be readjusting toward a slightly more southwest to northeast orientation. Manmade structures along all sections of the spit system will be subject to destruction during storms. The most stable unit, Nauset Spit-Eastham, appears to be undergoing a longer migration cycle than other sections of the spit system.

Artificial creation and maintenance of dunes and salt marshes can be used to extend various periods of the migration cycle but will not alter the basic biogeological process. With the initiation of a new inlet through North Beach, the town of Chatham will be subject to wave assault and severe erosion. Dune stabilization will not prevent the eventual formation of an inlet through this section of North Beach, which is eroding at a rate of 5.8 meters per year and is only 110 meters wide in some areas. Salt marshes cannot serve as an inlet deterrent because of the length of time required to establish a thick peat layer.

Nauset Spit-Orleans will also narrow through time until it will overwash, an inlet will form, and the spit north of Nauset Heights will be lost--perhaps fusing to Nauset Spit-Eastham as the inlet channel shifts. Dune stabilization along Nauset Spit-Orleans will only increase the rate of barrier narrowing as occasional overwash widening will be prevented.

Overwash will continue at Old North Beach and Nauset Spit-Eastham. Extensive dune stabilization can reduce overwash activity for a period of time resulting in calm back-barrier conditions necessary for the establishment of salt-marsh vegetation. Artificially established dunes will continue to narrow in the absence of washover sediment in upwind positions, and these foredunes will eventually be destroyed with incessant shoreline erosion. Salt-marsh peat behind the barriers will continue to restrict inlet formation.

Without artificial dune and salt-marsh establishment, new dunes and salt marshes will form along those parts of the barrier within the correct elevational ranges. However, it may be many years before high dunes are once again present on Nauset Spit-Eastham. A continuous dune line may not reform and appear as it did prior to 1978. New dunes, if artificially established, should be constructed well landward of the berm crest to allow for future shoreline erosion. Natural dunes will form toward the back of washovers in drift lines and expand eastward.

Salt marshes can also be established effectively on washover flats. Care should be taken to plant *Spartina patens* and *Spartina alterniflora* at elevations within their natural range along the spit system. Plantings should also be conducted only in areas that are not subject to continued overwash or high-energy conditions (swift currents near inlet channels or long fetch directions on the bay side).

Rapid shoreline erosion, high rates of littoral drift, and harbor conditions render rigid structures ineffective in a practical sense. By working in association with natural processes, segments of the migrational cycle can be expanded but not restricted.

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